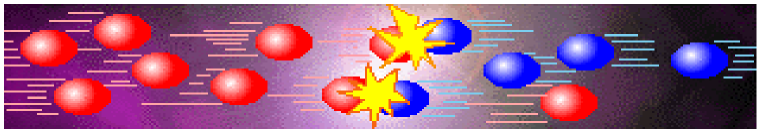


Hadron Collider Physics

Jianming Qian
University of Michigan

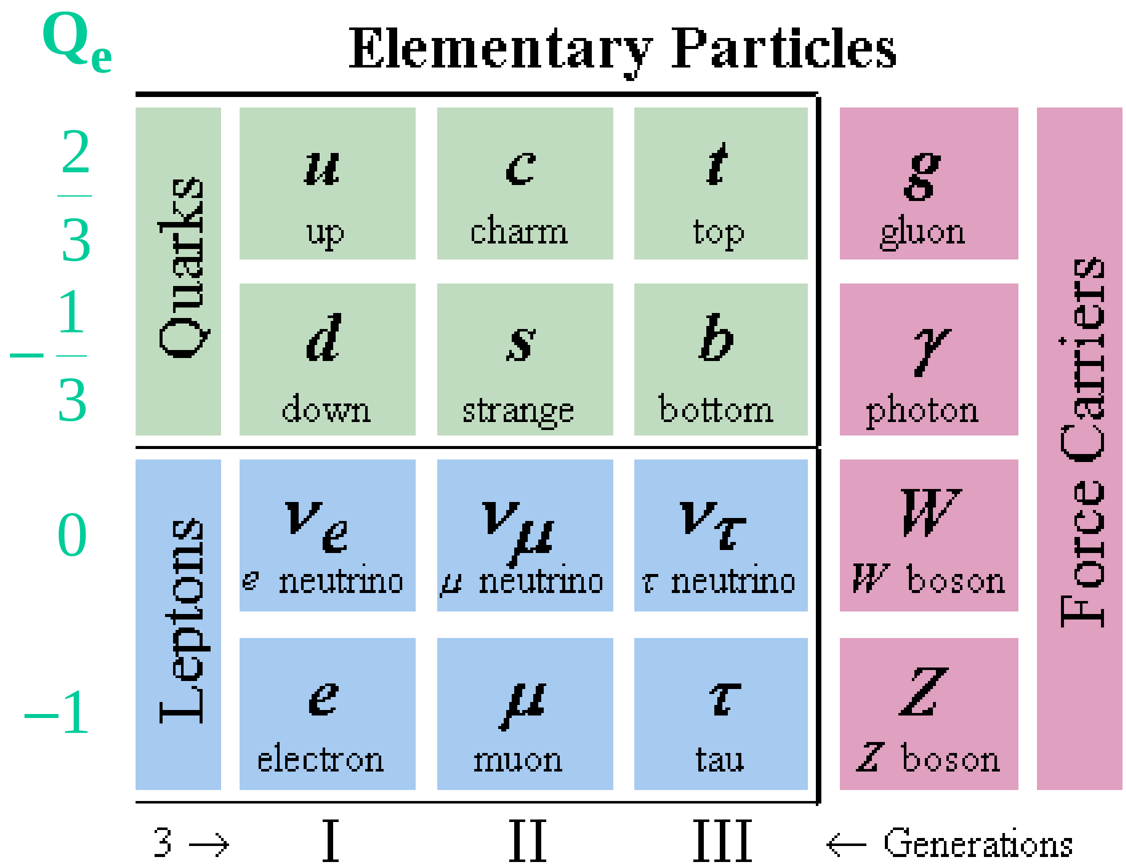
1) What we do and do not know
2) Apparatus we use
3) Present Results
4) Future Expectations

Department Colloquium
October 21, 1998

What We Know

The Standard Model is the theory describing the interactions (strong, electromagnetic and weak) among elementary particles

Elementary particles come in two varieties
Fermions (quarks & leptons) and Gauge Bosons



increasing in mass

The electroweak symmetry requires particles to be massless and therefore must be broken

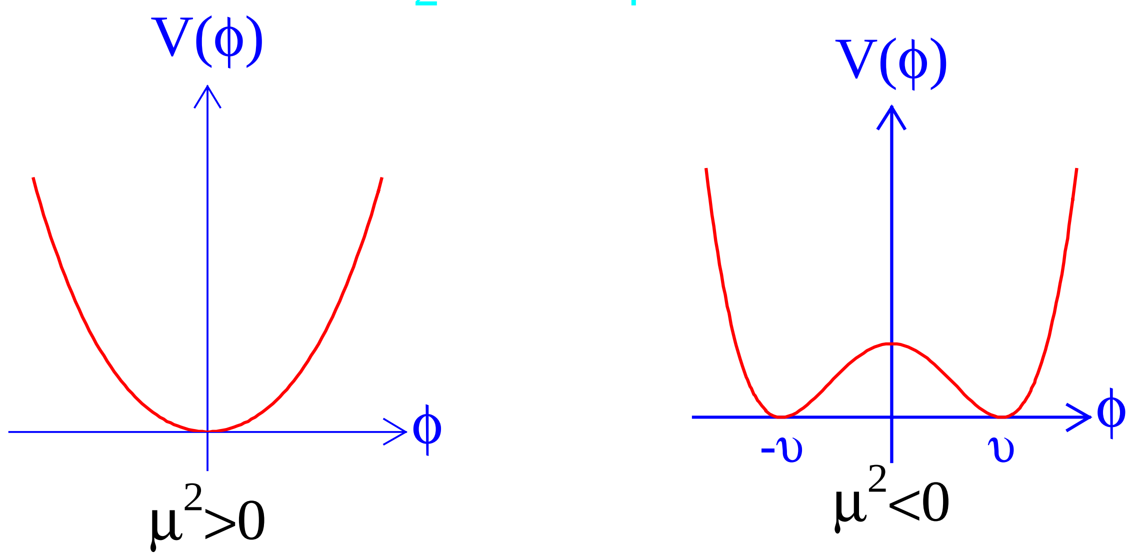
SM is a gauge theory with symmetry groups
$SU(3)_C \otimes SU(2)_L \otimes U(1)_Y$

Higgs Mechanism

The electroweak symmetry is postulated to be broken through the Higgs mechanism

Consider a scalar particle ϕ with potential

$$V(\phi) = \frac{1}{2}\mu^2\phi^2 + \frac{1}{4}|\lambda|\phi^4$$



The ground state does not possess the $\phi \to -\phi$ symmetry of the potential if $\mu^2 < 0$

Consequences of EW symmetry breaking

1) The mediators of weak interactions ($W^\pm$ and Z) acquire masses.
2) Electromagnetism is mediated by massless photon.
3) At least one massive neutral scalar particle (Higgs particle) appears, but its mass is not predicted.
4) Fermions can acquire mass through their Yukawa couplings to the Higgs.

What We Do Not Know

Though there are no confirmed data that deviate from
the Standard Model, nevertheless
there are many open questions within the model

Top Quark

Does it decay according to the Standard Model expectation?
Why is it so much heavy than other quarks?
Does it have structure?
Does it play a role in electroweak symmetry breaking?
……

Higgs Mechanism

Does Higgs Boson exist?
What is the origin of electroweak symmetry breaking?
What is the origin of fermion masses and
their pattern?
……

Bottom Quark

Is CP violated in b-quark decays?
……

Neutrinos

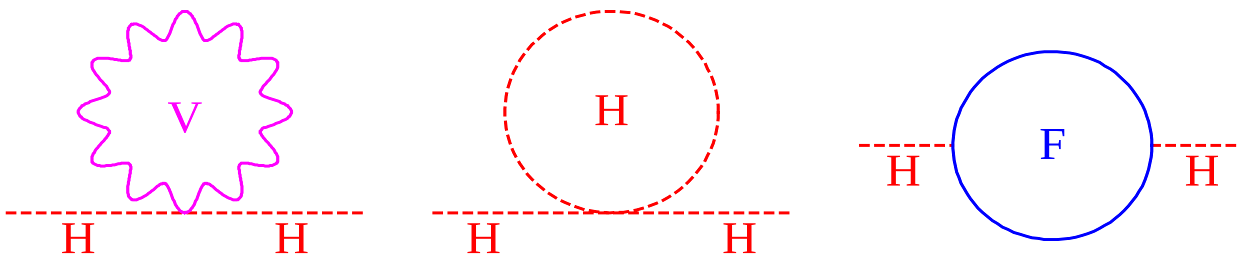
Despite of recent breakthrough, it is fair
to say that we still don't understand neutrinos

……

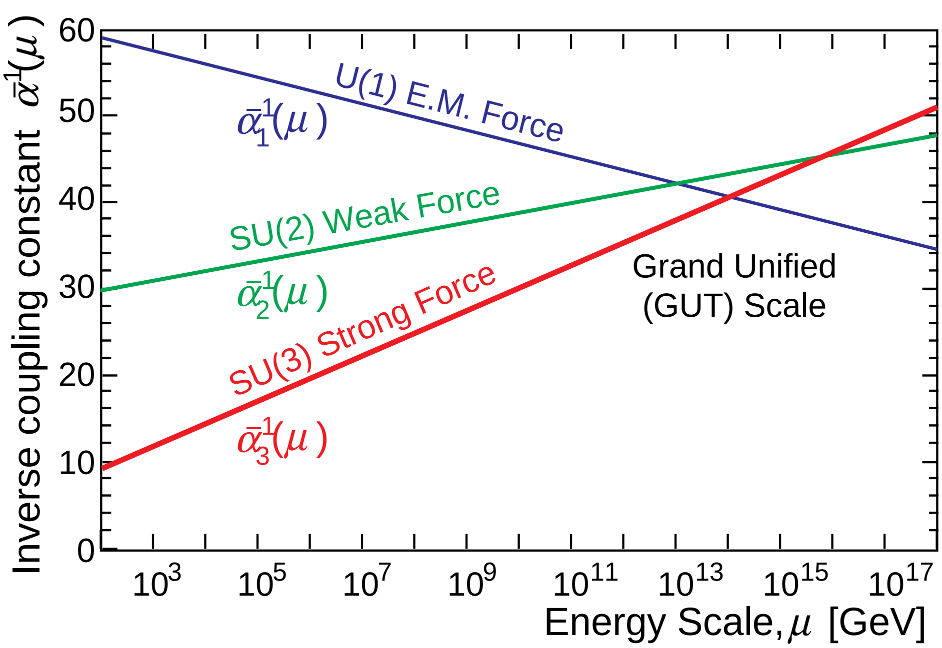
Theoretical Issues

Theoretically, the Standard Model is unlikely to be a complete theory

Higgs boson mass receives radiative corrections which are quadratically divergent

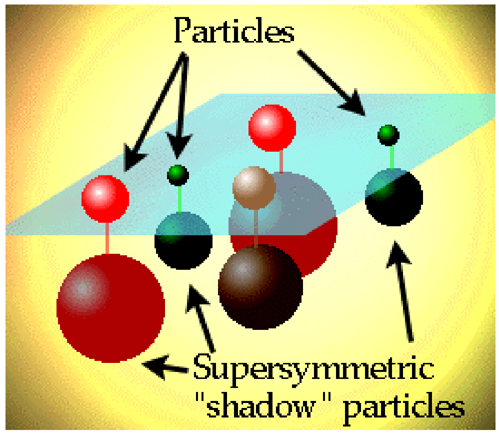


Not only Standard Model does not incorporate gravity, strong, electromagnetic and weak interactions do not unify at high energies without new physics



Beyond the Standard Model

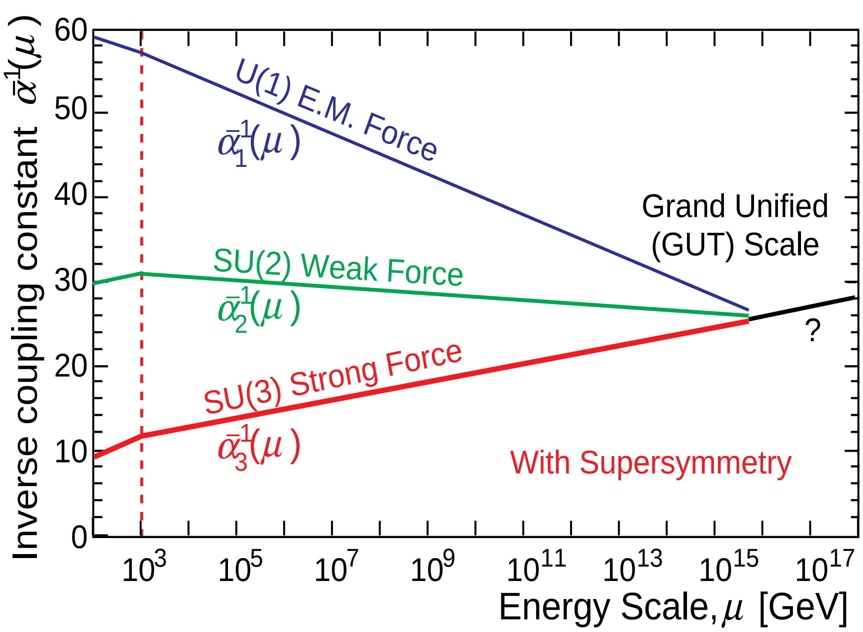
Supersymmetry is a theory that theoretically popular
but experimentally unconfirmed



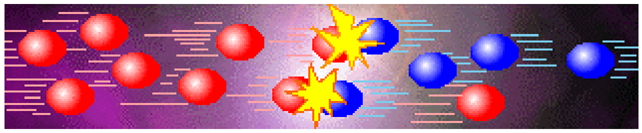
It provides a solution to Higgs mass problem
by equalizing numbers of fermions and bosons

It offers a path to the incorporation of gravity

Strong, electromagnetic and weak forces unify
at high energies with supersymmetry

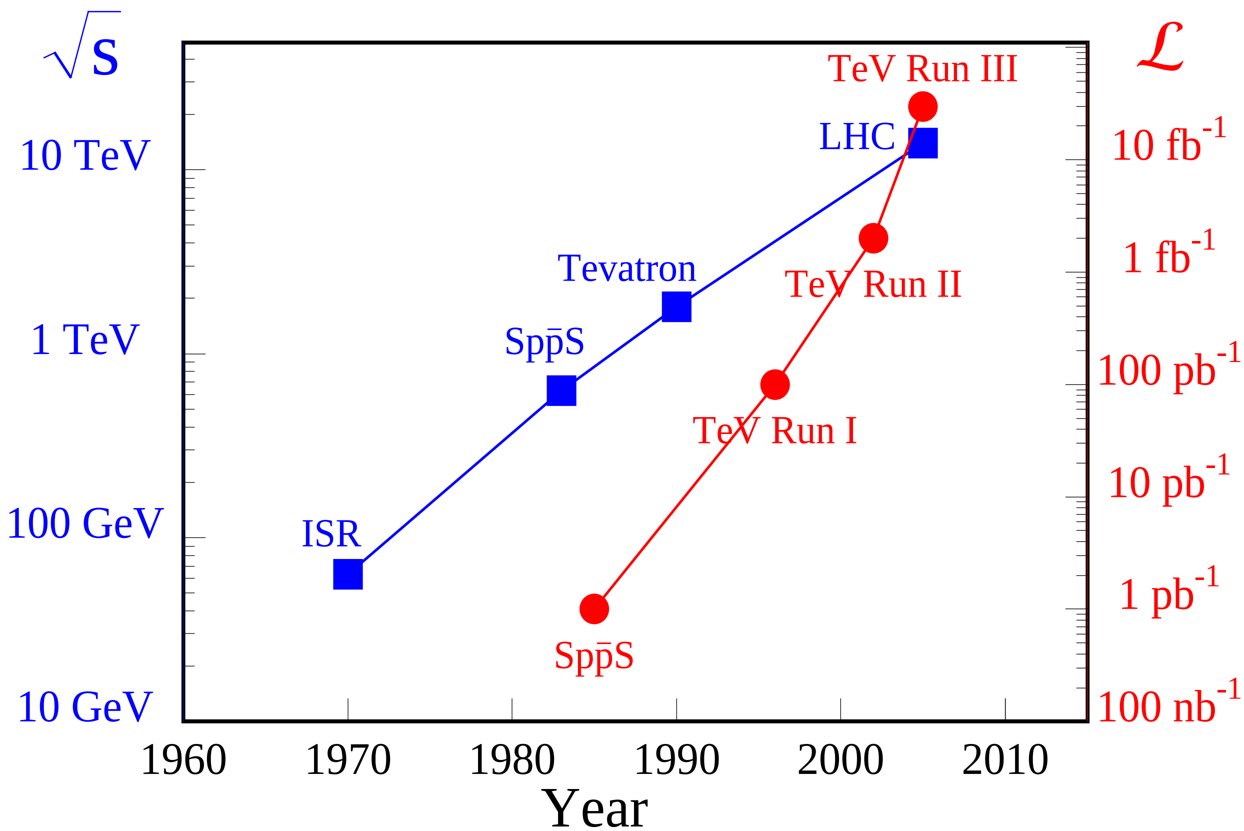


Hadron Collider Chronicle

p  $\bar{p}$ (p)

Two most important parameters
Center – of – mass energy ($\sqrt{s}$) and Luminosity ($\mathcal{L}$)

# of observed events =
Luminosity × Cross Section × Efficiency = $\mathcal{L} \times \sigma(\sqrt{s}) \times \varepsilon$



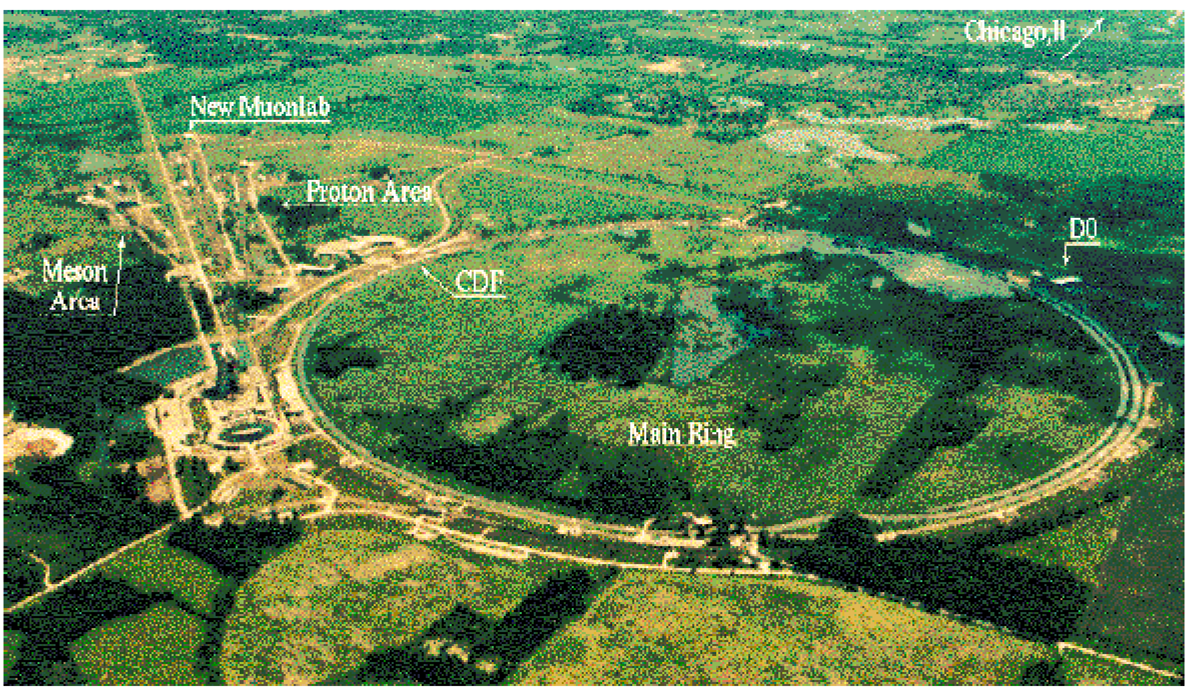
1970 : ISR at CERN	pp	high p_T physics
1982 : Sp$\bar{p}$S at CERN	p$\bar{p}$	W/Z discoveries
1990 : Tevatron at Fermilab	p$\bar{p}$	top discovery...
2005 : LHC at CERN	pp	???

Tevatron $p\bar{p}$ Collider

Fermilab Tevatron Collider is the highest energy collider currently in operation in the world

Proton and anti-proton beams were accelerated to 900 GeV each and were brought to collide at 2 interaction points (CDF and DØ)

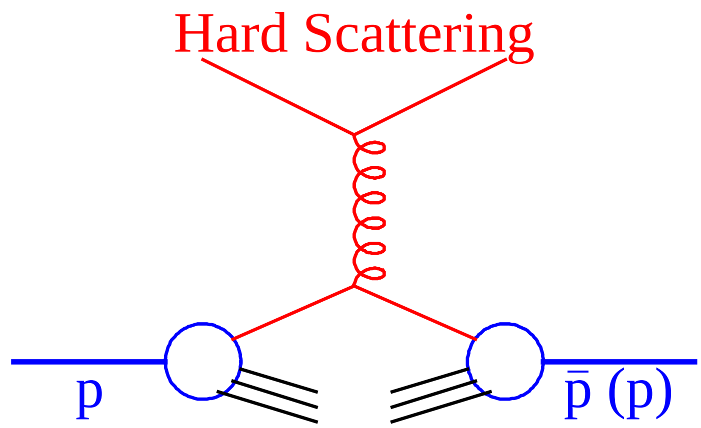
Run I (1990-1996)
An integrated luminosity of about 100 pb^{-1} was recorded per detector



Hadron Collision Kinematics

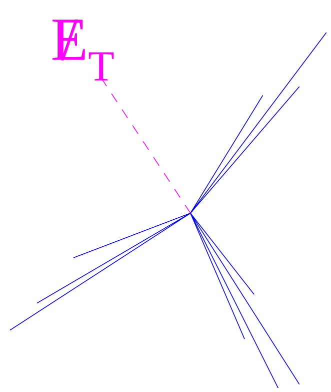
Protons (antiprotons) are composite particles

For the purpose of hard scattering,
a proton (anti-proton) is a broad-band, unselected beam
of quarks, anti-quarks and gluons.



Total energy is unknown
Total longitudinal momentum is unknown
Total transverse momentum is zero

The total transverse energy of invisible particles
can be inferred from visible particles



(Transverse Plane)

$$\sum_{\text{inv}} \vec{E}_T + \sum_{\text{vis}} \vec{E}_T = 0$$

$$\vec{\not{E}}_T \equiv \sum_{\text{inv}} \vec{E}_T = -\sum_{\text{vis}} \vec{E}_T$$

From Collision to Detection

Particle Decays

Heavy quarks/leptons are unstable and decay
via weak interaction to their
lighter counterparts whenever kinematically allowed

2/3	u	c	t
–1/3	d	s	b
0	ν_e	ν_μ	ν_τ
–1	e	μ	τ

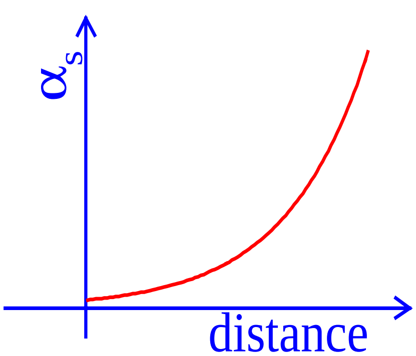
$t \to bW$	$c\tau \sim 1\,\mathrm{fm}$	(prompt)
$b \to cW^*$	$c\tau \sim 470\,\mu\mathrm{m}$	(delayed)
$\tau \to \nu_\tau W^*$	$c\tau \sim 90\,\mu\mathrm{m}$	(delayed)
$\mu \to \nu_\mu W^*$	$c\tau \sim 650\,\mathrm{m}$	(stable)

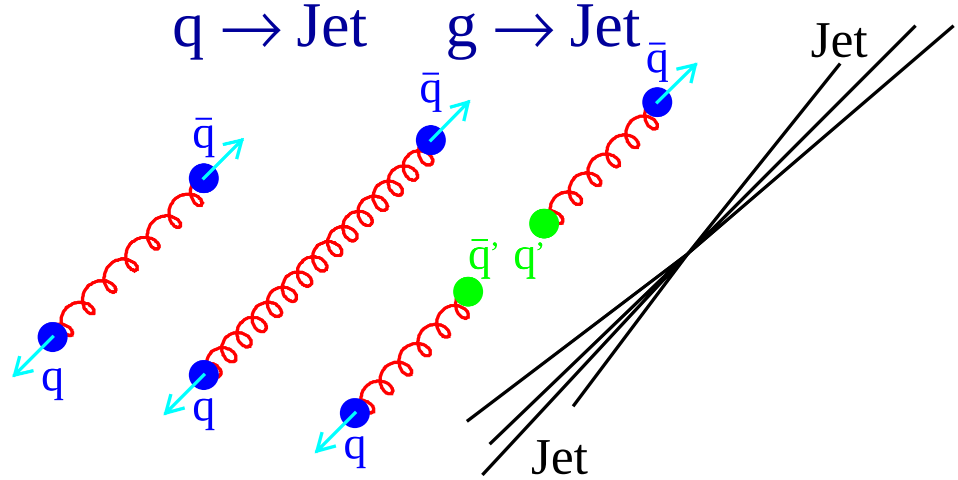
$$W \to q\bar{q}',\ \ell\nu$$

Hadronization

No free quark or gluon has ever been observed
An energetic quark or gluon appears in a detector as
a jet of colorless hadrons

$q \to \mathrm{Jet}$ $\quad g \to \mathrm{Jet}$

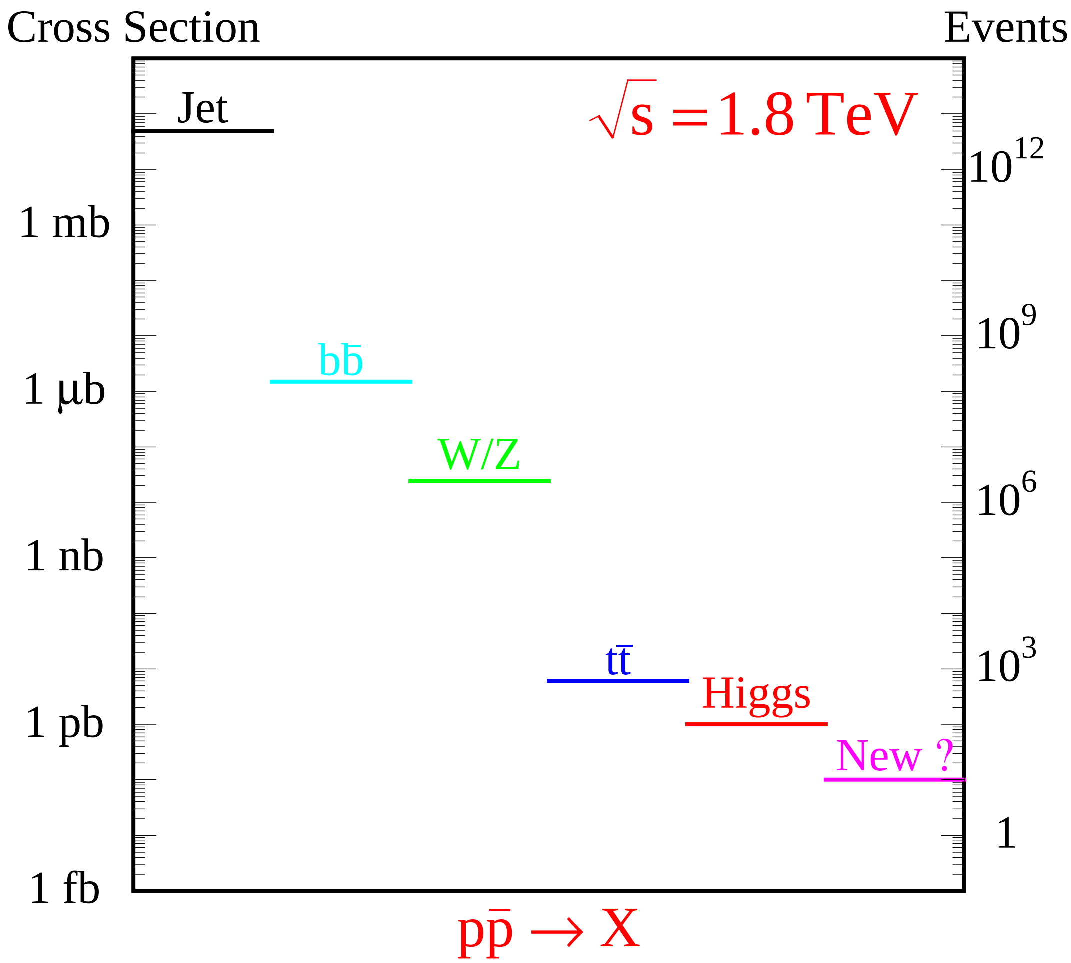




Occur at an energy scale Λ_{QCD}

Cross Sections

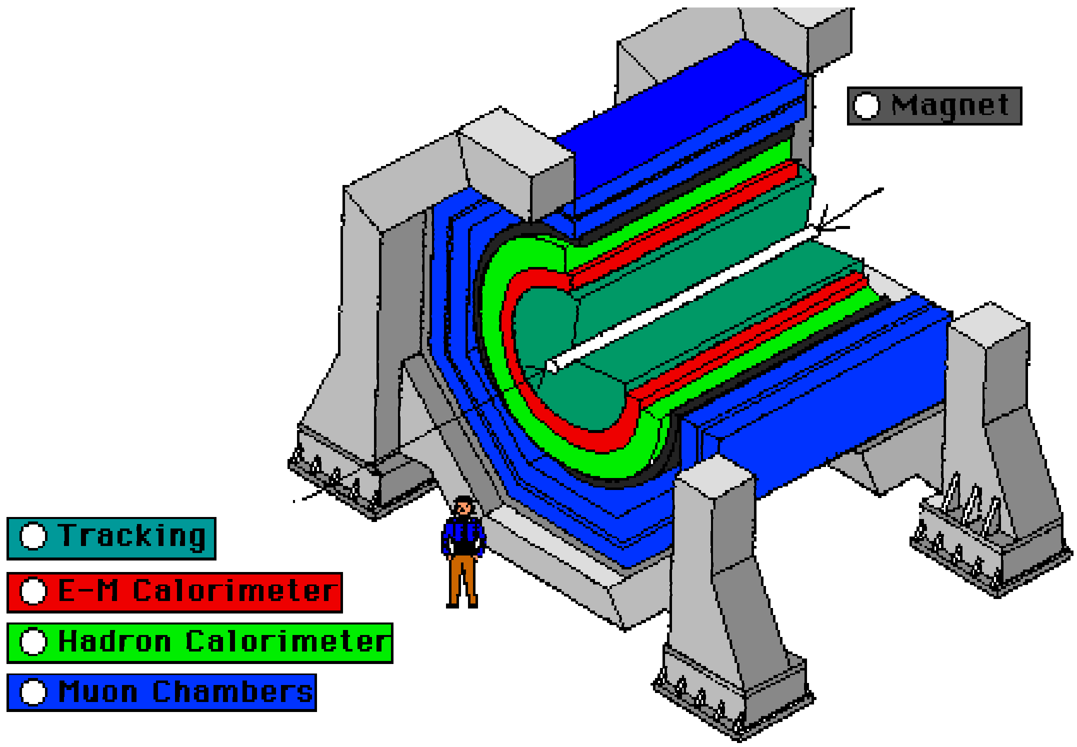
The cross section is dominated by jet production.



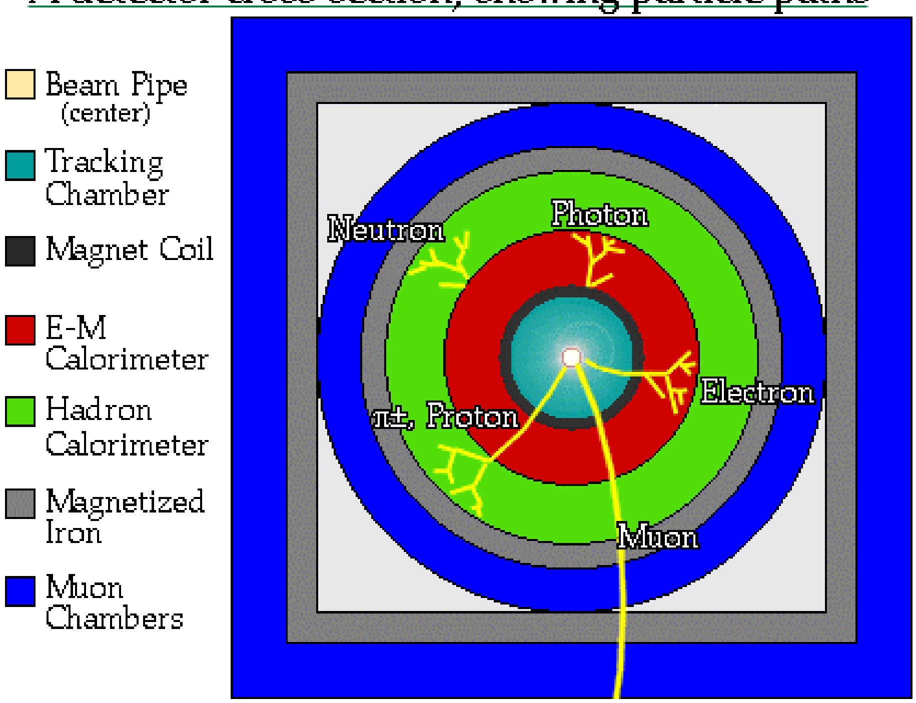
Interesting high p_T events are buried in huge backgrounds

One of the challenges is to reduce backgrounds to acceptable levels through successive hardware and software algorithms

Collider Detector



A detector cross-section, showing particle paths



Identified objects

$e, \mu = \text{Lepton} (\ell)$

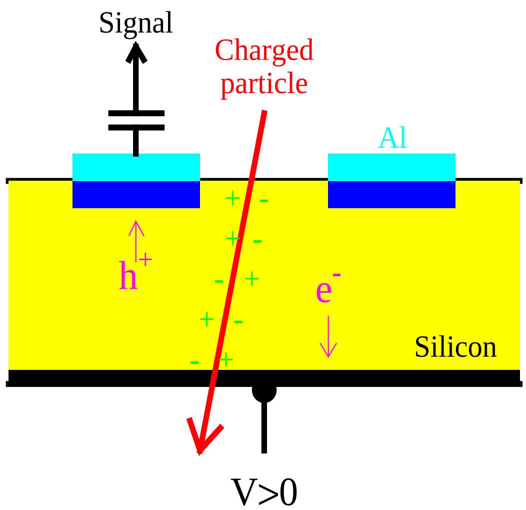
$\gamma = \text{Photon}$

$q, g = \text{Jet}$

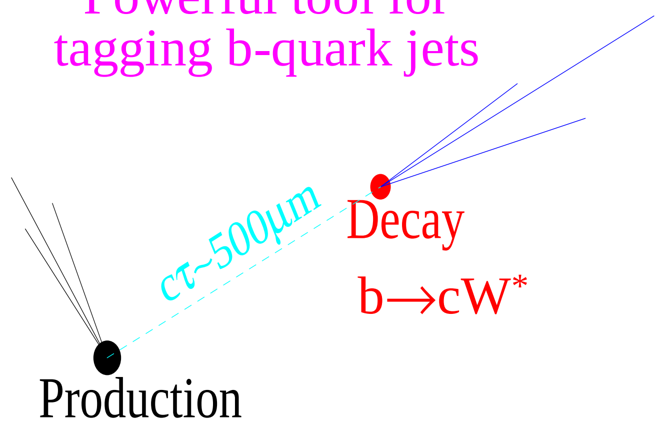
$\nu \text{ and...} = \not{E}_T$

Silicon Detector

The development of the silicon detector represents one of the greatest advance in detector technology



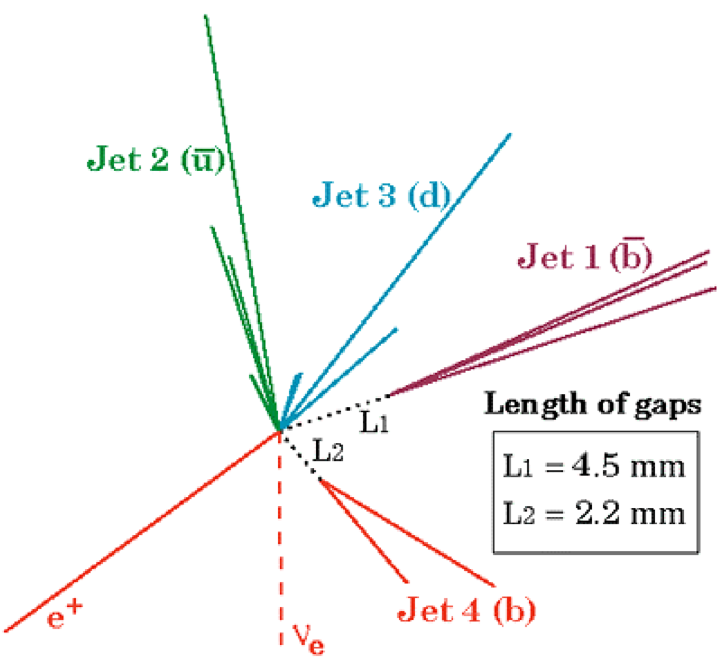
Powerful tool for tagging b-quark jets



$p + \bar{p} \longrightarrow t + \bar{t}$

$t \longrightarrow b + W^+$ $\quad W^+ \longrightarrow e^+ + \nu_e$

$\bar{t} \longrightarrow \bar{b} + W^-$ $\quad W^- \longrightarrow \bar{u} + d$



A CDF $t\bar{t}$ candidate

Both b-quark jets are tagged by their decay vertices

The event gives m_{top}=170±10 GeV

DØ Collaboration

About 450 physicists from 48 institutions of 11 countries

<u>UM/DØ Group Members</u>

Faculty
H. Neal, J. Qian, B. Zhou

Research Fellows
K. Del Signore, A. Turcot, (N. Amos, D. Stewart)

Graduate Students
W. Chen, Y. Huang, Q. Xu, (F. Hsieh, S. Chopra)

Major Michigan Projects

Infrastructure Contributions

Run I: InterCryostat Detector
(H. Neal et al.)

Run II: Central Preshower Detector
(K. Del Signore, D. Lincoln, J. Qian, ...)

Particle Identification Software Development
(K. Del Signore, A. Turcot)

Physics Activities

Ph.D. Thesis Analyses

Measurement of $t\bar{t}$ cross section and
Search for new physics beyond the Standard Model
(Sailesh Chopra)

Measurement of Top Quark Mass
(Frank Hsieh)

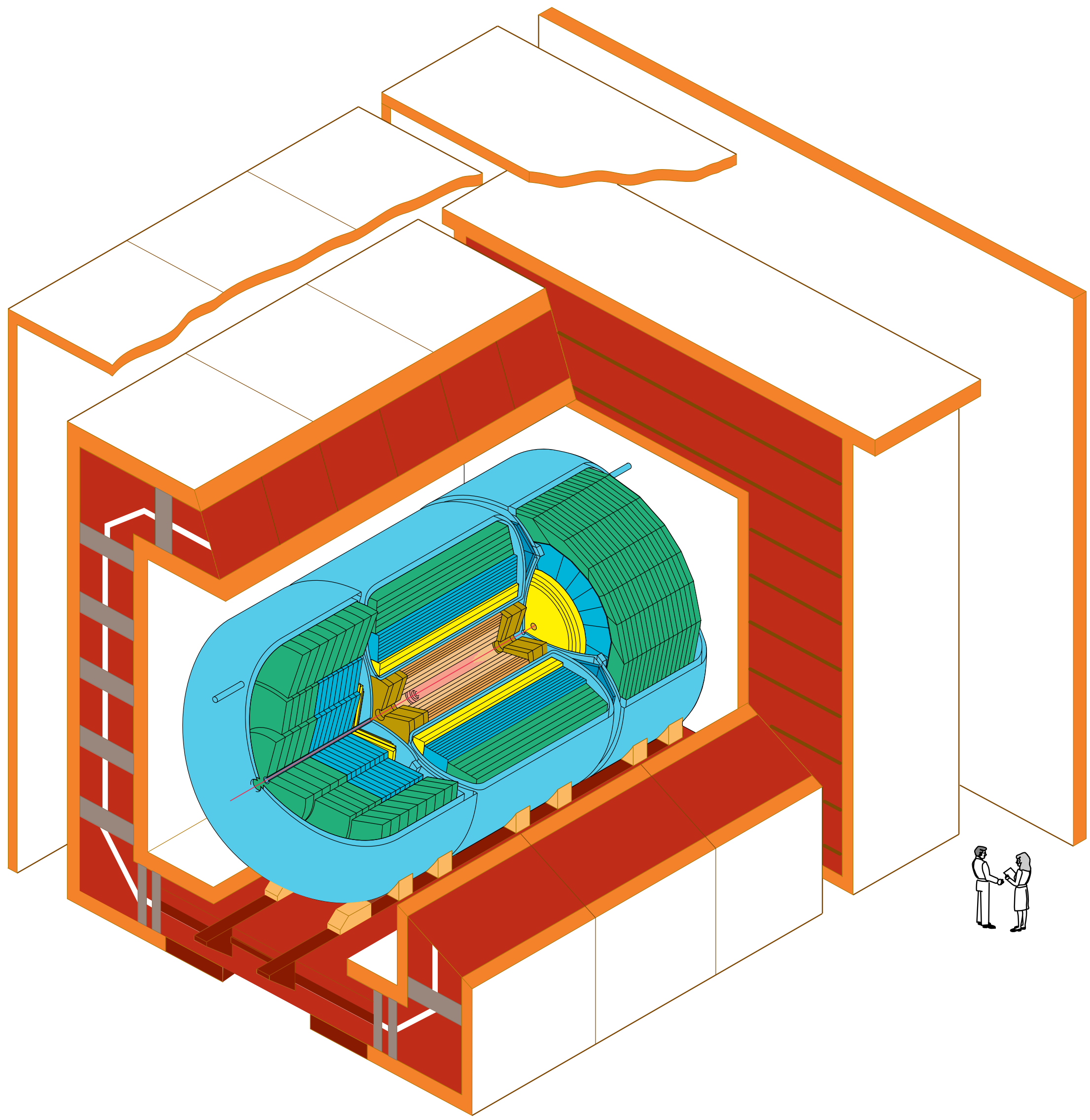
Other Analyses

Search for Top Quark in All-jets Final State
(N. Amos, D. Stewart)

Search for Supersymmetry with Photons
(S. Chopra, J. Qian)

Run II Higgs/Supersymmetry Studies
(J. Qian, A. Turcot)

Run I Detector



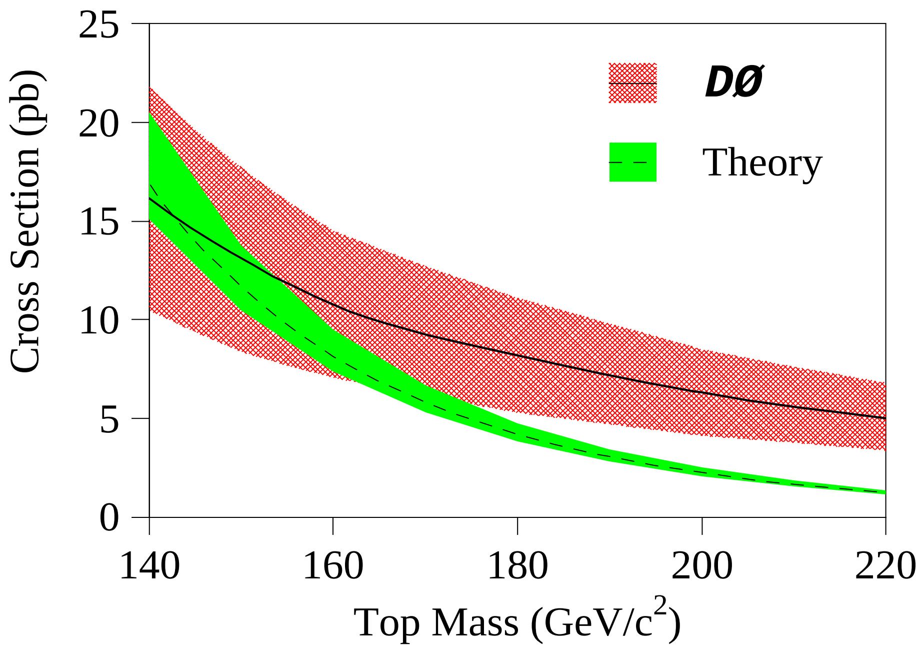
DØ detector is a nonmagnetic detector.
It emphasizes calorimetric detection of jets and $\not{E}_T$.
It is designed for studying high p_T phenomena.

The key component is the uniform, hermetic
and fine-segmented liquid Argon/Uranium calorimeter

Discovery of the Top Quark

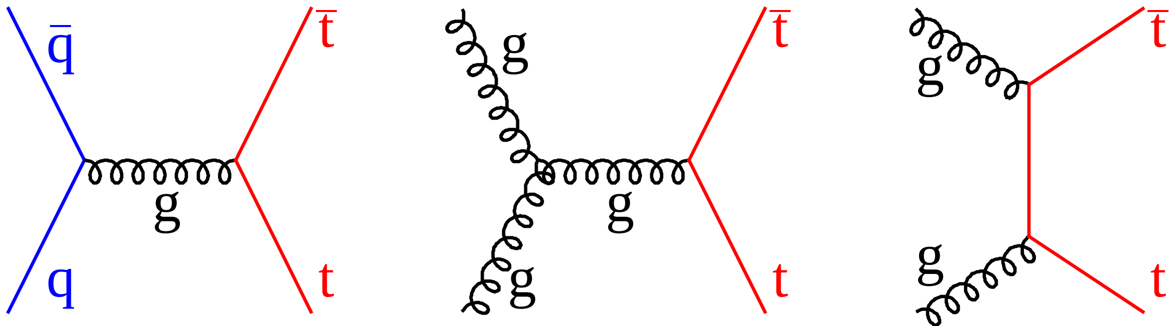
CDF: *Phys. Rev. Letters 74, 2626 (1995)*
DØ: *Phys. Rev. Letters 74, 2632 (1995)*

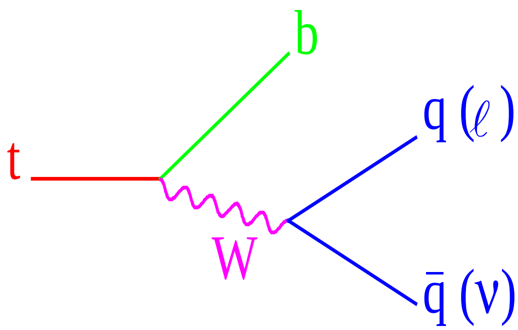
	Standard Cuts	Loose Cuts
Dilepton	3	4
ℓ + jets (topo)	8	23
ℓ + jets (b tag)	6	6
Total	17	33
Background	3.8±0.6	20.6±3.2
Probability	2×10^{-6} (4.6σ)	0.023 (2.0σ)
σ_{tt} (m_t=200)	6.3±2.2 pb	4.5±2.5 pb



Top Quark Production

Top quarks are mostly pair produced at Tevatron





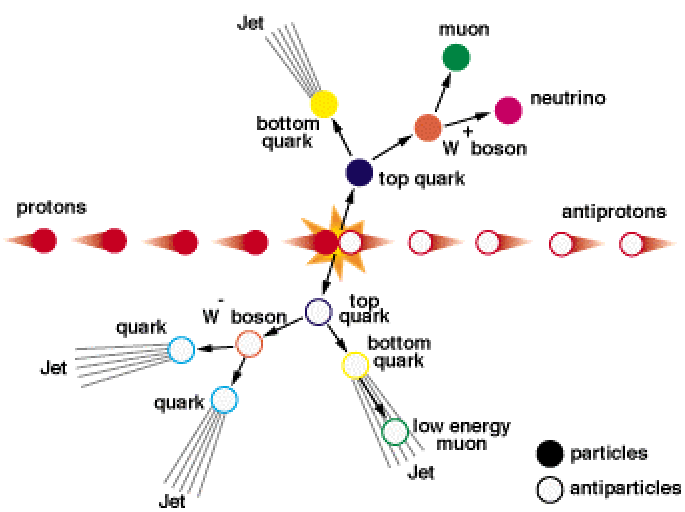
Top is short lived: $t \to Wb$

$(W \to \ell\nu, W \to \ell\nu) \Rightarrow \ell\ell$

$(W \to \ell\nu, W \to qq') \Rightarrow \ell + \text{jets}$

$(W \to qq', W \to qq') \Rightarrow \text{All - jet}$

A schematic μ + jets event from $t\bar{t}$ decays



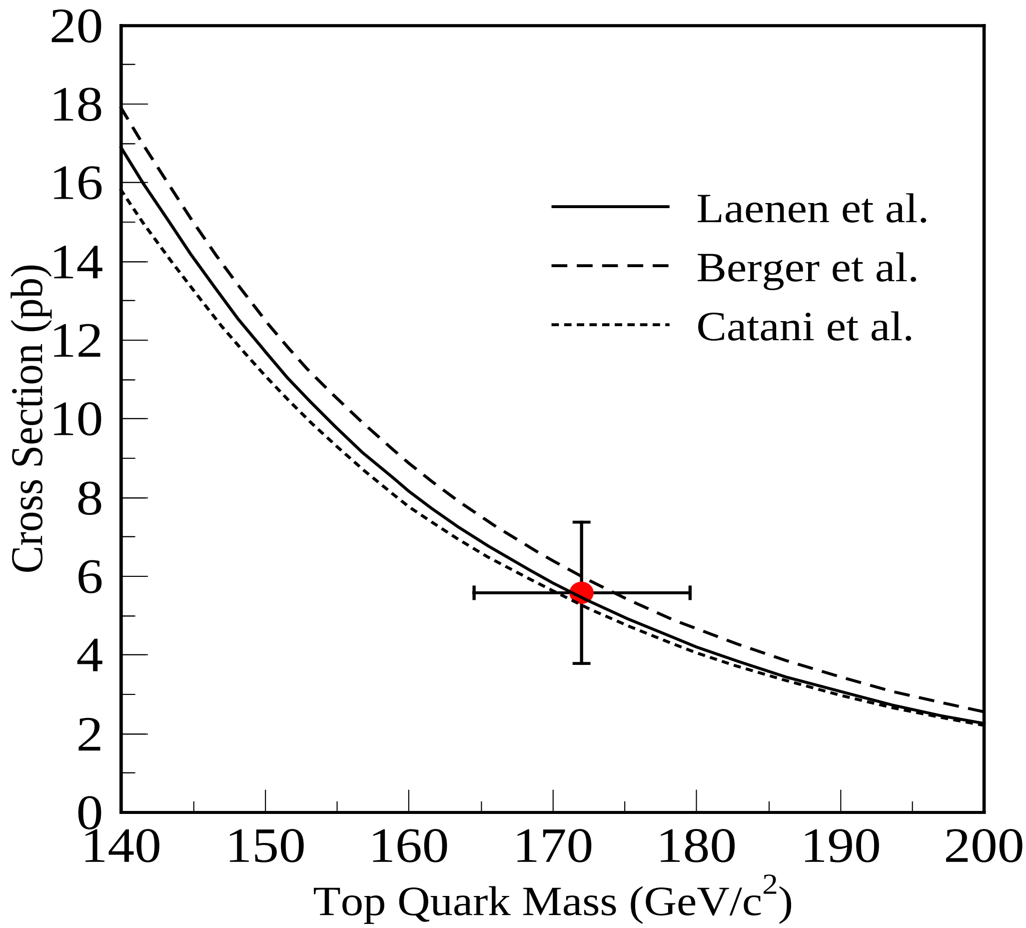
A Top Antitop Quark Event from the D-Zero Detector at Fermilab

Top pair production is a rare process

For every top pair event, there are about 1,000,000,000 other events produced

$t\bar{t}$ Production Cross Section

$$\text{Cross Section} = \frac{N_{event} - N_{background}}{\text{Luminosity} \times \text{Efficiency}}$$



$$\sigma(p\bar{p} \to t\bar{t} + X) = 5.5 \pm 1.8\ \text{pb}$$

Based on a sample of about 40 tt candidates

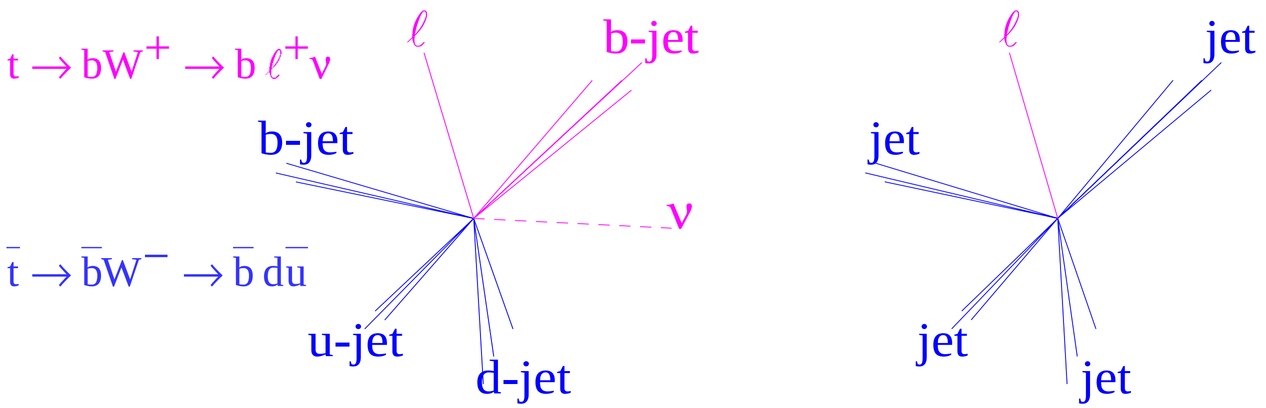
Phys. Rev. Lett. 79, 1203 (1997)

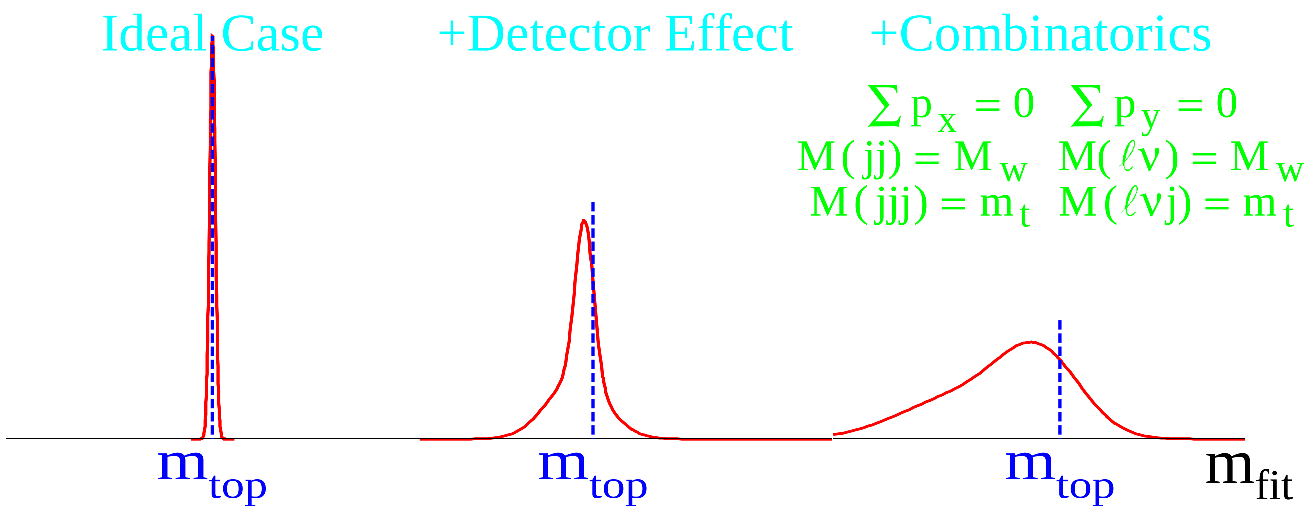
Measured cross section is in good agreement with all three Next-Leading-Order calculations

Weighing Top Quark

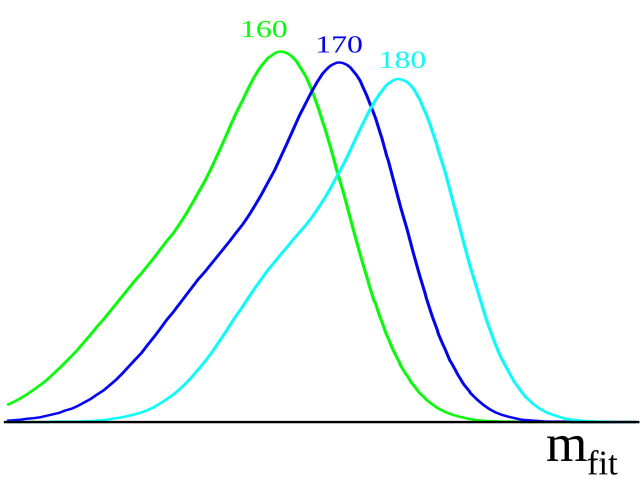
ℓ + jets $t\bar{t}$ candidates

What happened | What we observed





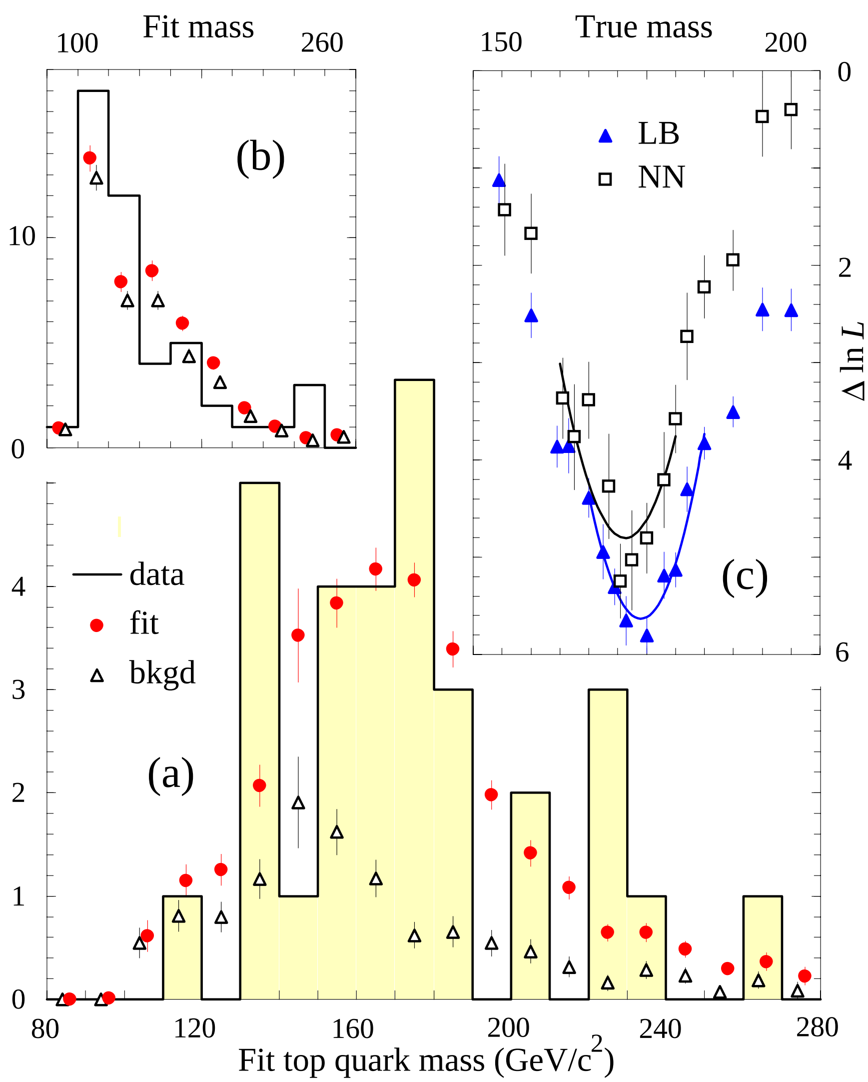
Monte Carlo Templates



The m_t can be extracted by comparing the measured m_{fit} distribution with the signal templates obtained from Monte Carlo

Top Quark Mass

Data (ℓ + jets) are divided into
top - rich and background - rich regions

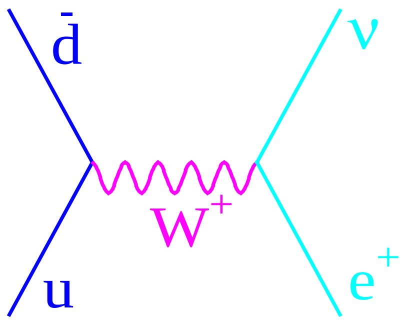


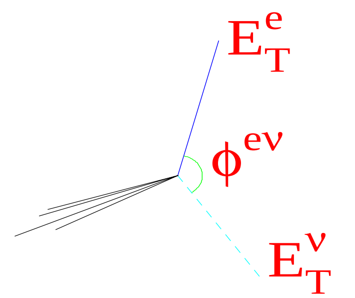
A likelihood fit to fitted mass distribution with a mixture of top signal and background distributions yielded

$$m_t = 173.3 \pm 5.6(\text{stat}) \pm 5.9(\text{syst})\ \text{GeV}/c^2$$

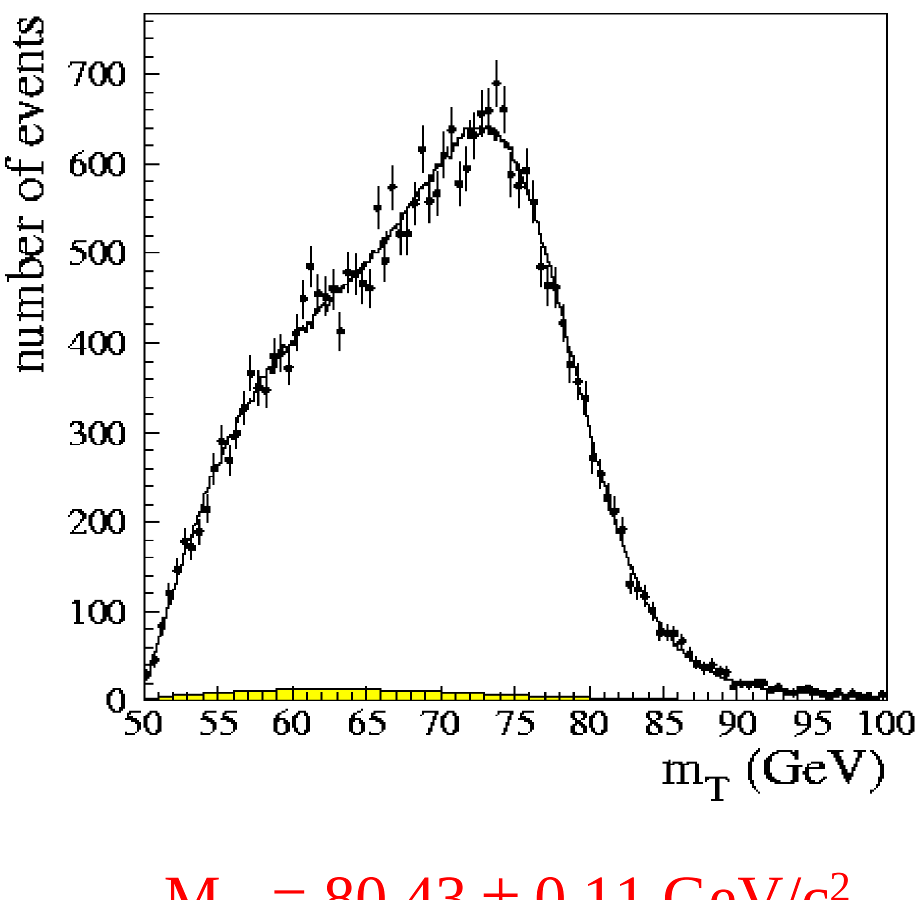
Phys. Rev. Lett. 79, 1197 (1997)

W Boson Mass





Transverse mass $m_T = \sqrt{2E_T^e E_T^\nu (1 - \cos\phi^{e\nu})}$



$M_W = 80.43 \pm 0.11$ GeV/c^2

Phys. Rev. Lett. 80, 3008 (1998)

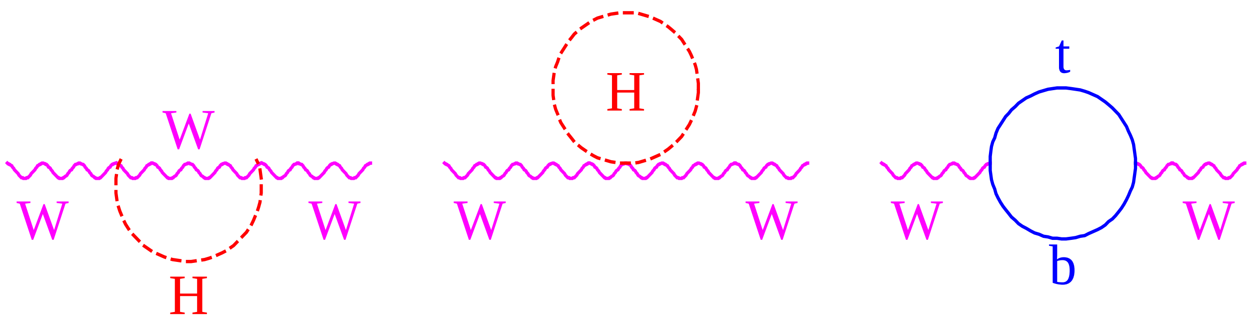
The error is presently dominated by statistics

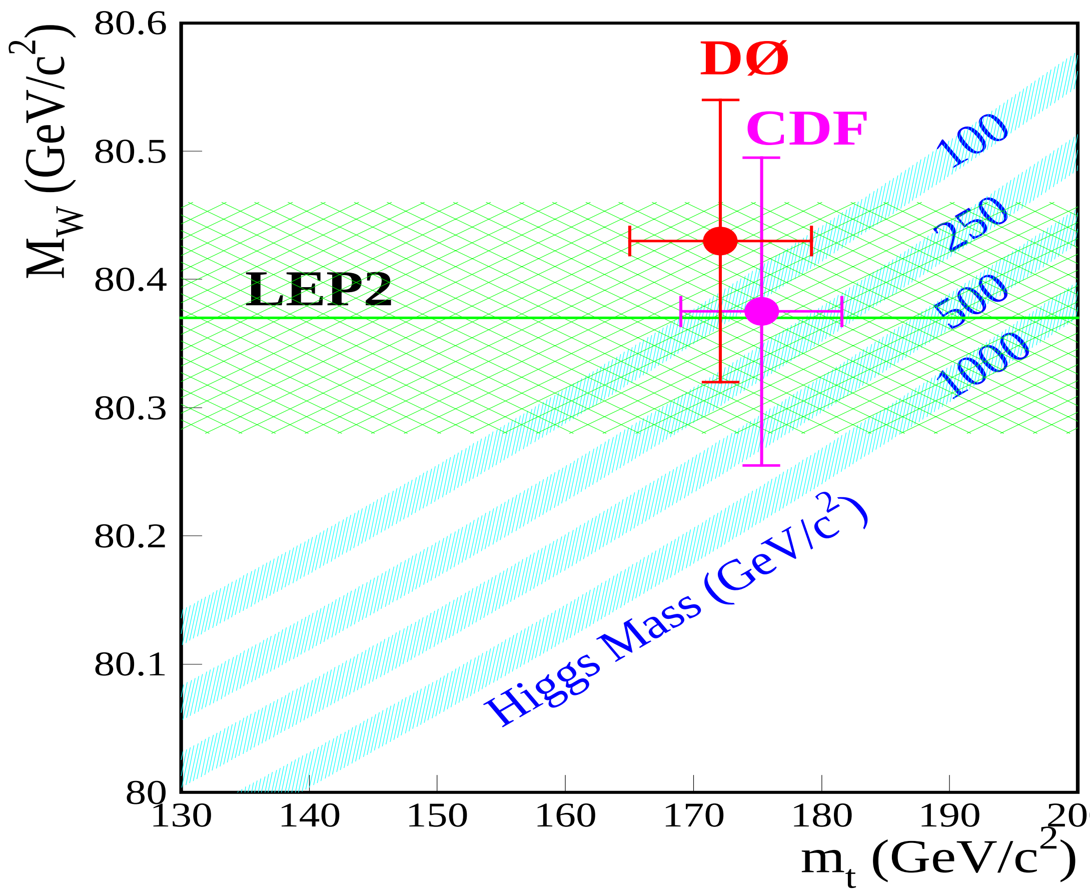
Electroweak Corrections

Within the Standard Model

$$M_W^2 = M_Z^2(1 - \sin^2\theta_W)(1 + \Delta\rho)$$

Radiative correction $\Delta\rho = \Delta\rho(m_t, M_H, \alpha, \ldots)$

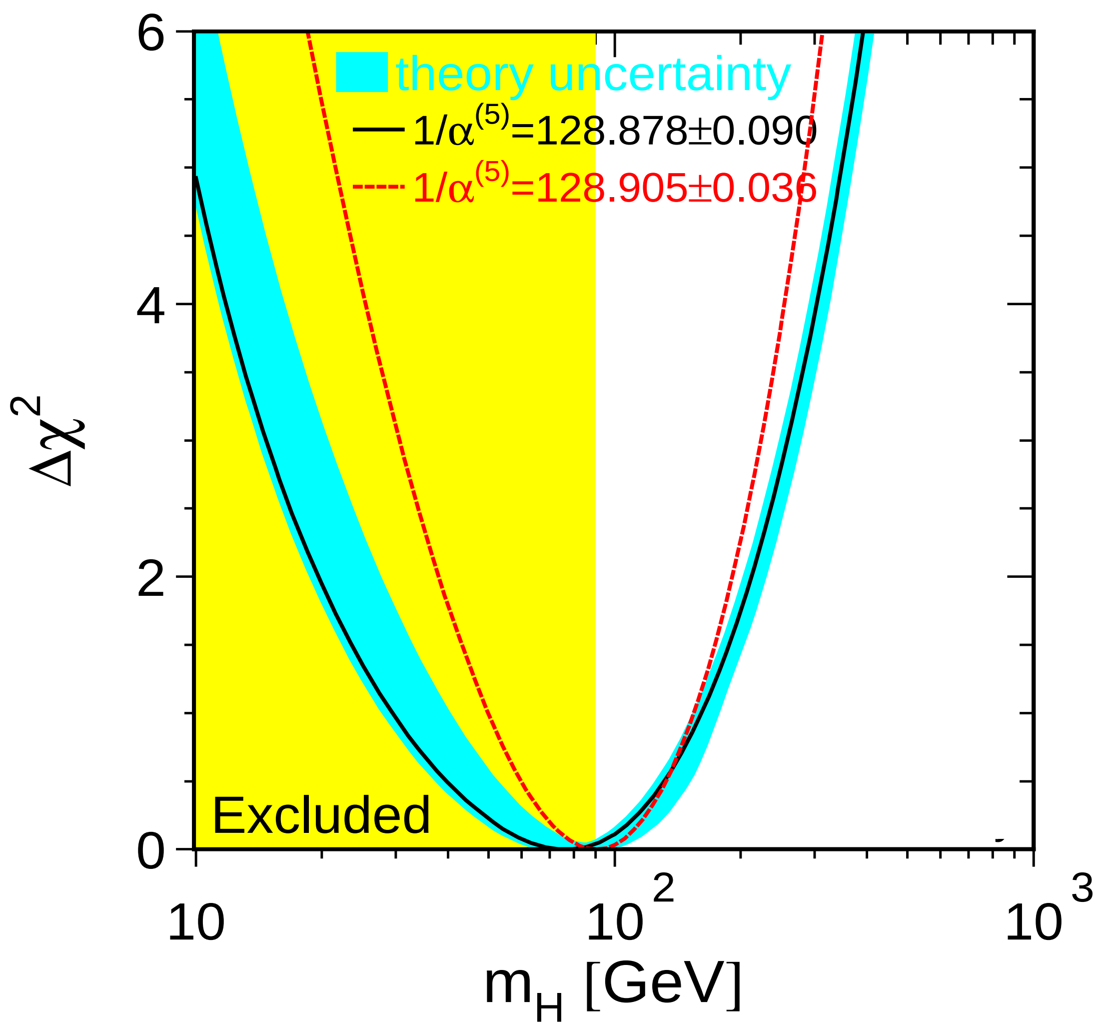




By measuring top quark and W boson masses precisely, the Higgs boson mass can be extracted

Standard Model Fit

Global fit to all precision data
(LEP, SLC, Tevatron, …)
with Higgs boson mass as the free parameter



The fit prefers a low mass Higgs !

The direct searches at LEP
$M_H > 90\ \mathrm{GeV}/c^2$ at 95% C.L.

m_t From SM Fit

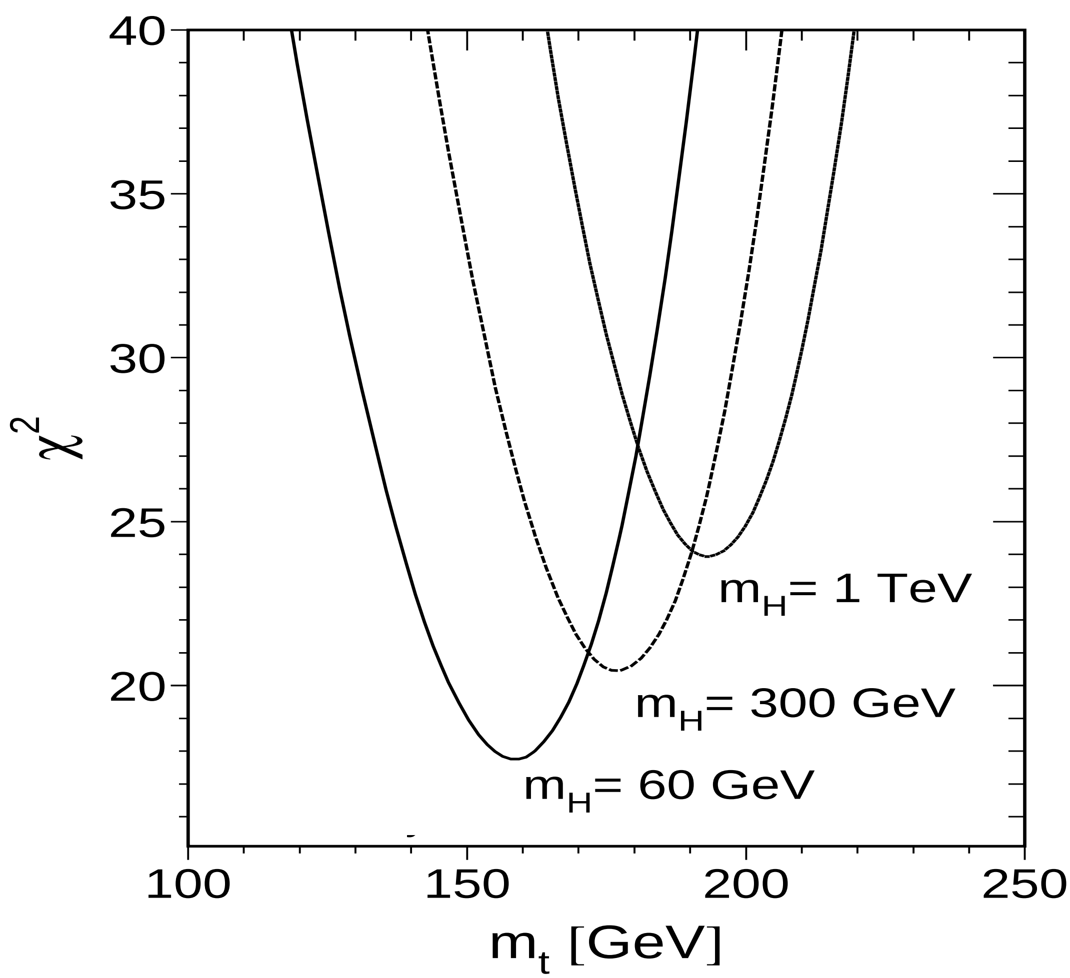
Before the top quark discovery, the top quark mass was inferred from the precision data to be

$$m_t = 177 \pm 11 \pm 19 \ \ \mathrm{GeV}/c^2$$

(B. Jacobsen, XXIXth Rencontre de Moriond, 1994)

To be compared with the direct measurements of CDF/DØ

$$m_t = 174 \pm 5\ \mathrm{GeV}/c^2$$



(JQ, Ph.D. Thesis, MIT, 1990)

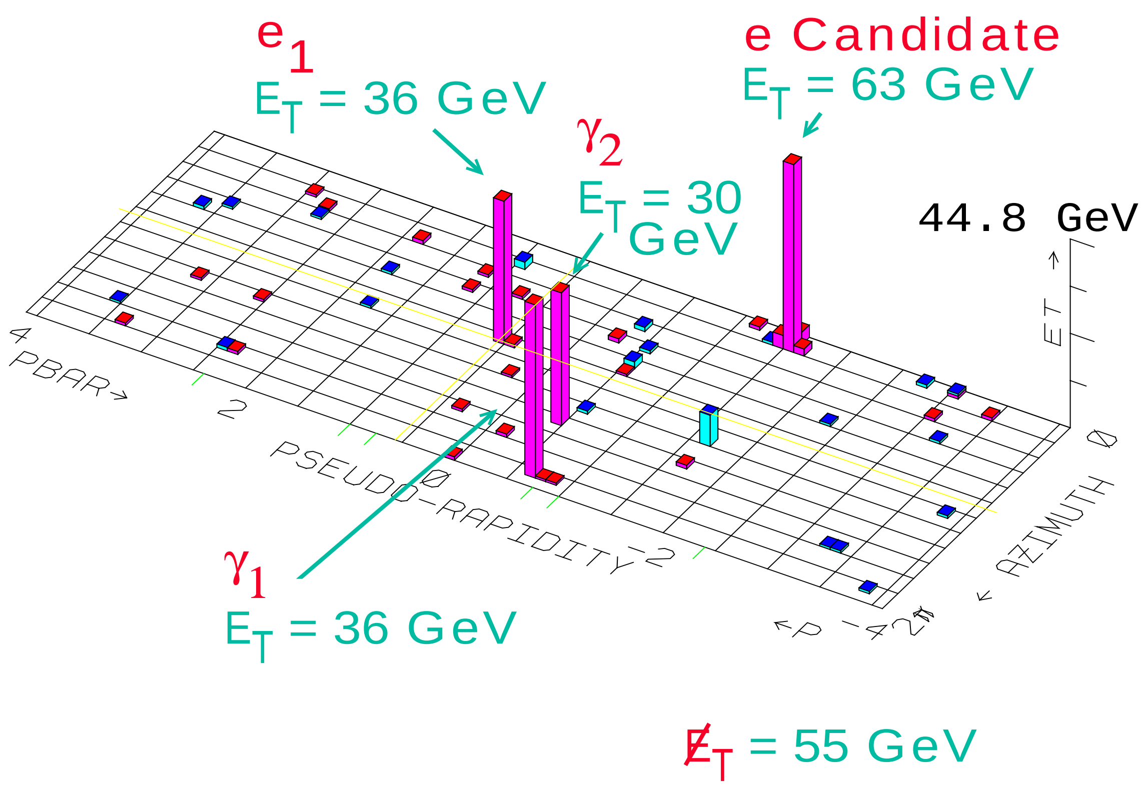
$$m_t = 125 \pm 35 \pm 20\ \mathrm{GeV}/c^2$$

CDF $ee\gamma\gamma \not{E}_T$ Event

Much publicity has accompanied the CDF event.

It is unusual because isolated leptons, photons,
and especially large $\not{E}_T$ are rare in the Standard Model

$ee\gamma\gamma \not{E}_T$ Candidate Event



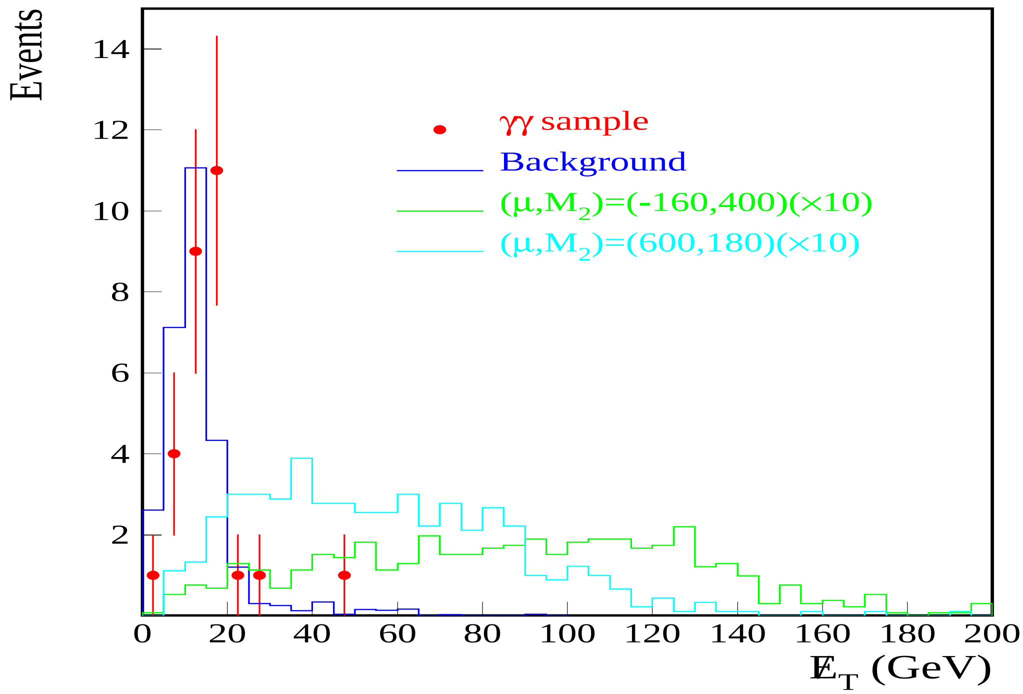
The probability for the event to be resulted from known process is estimated to be 10^{-6}.

Phys. Rev. Lett. 81, 1791 (1998)

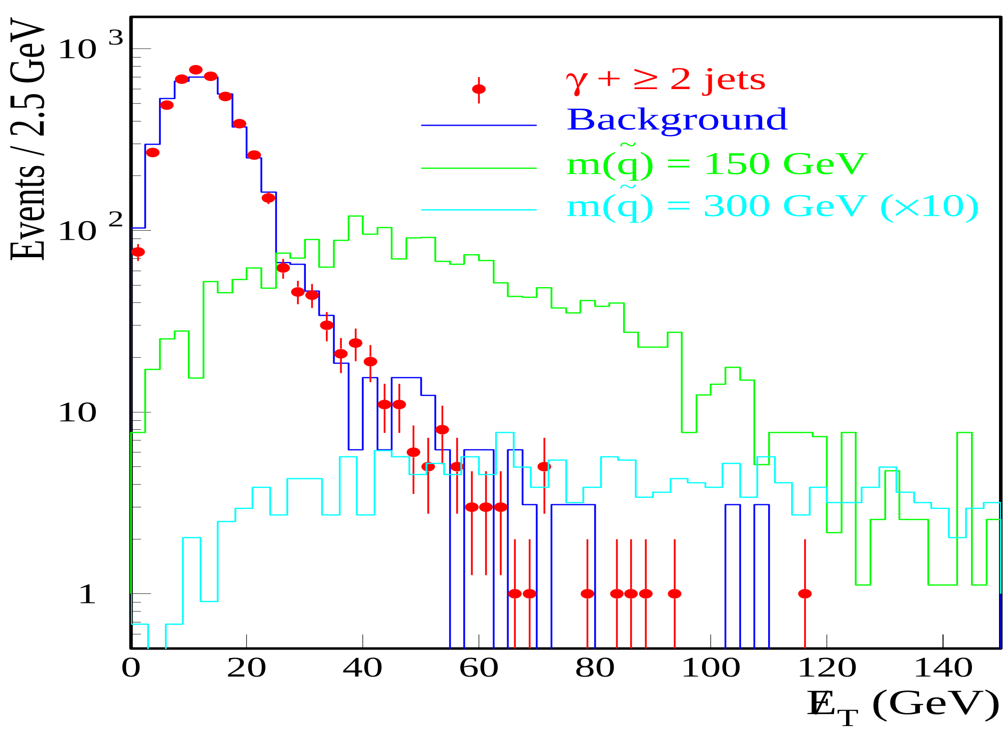
It generated considerable theoretical interest

Search for $\gamma(\gamma)\not\!\!E_T$ Events

DØ searched for $\gamma\gamma\not\!\!E_T$ and $\gamma\not\!\!E_T$+jets events and
no excess beyond the backgrounds was observed



Phys. Rev. Lett. 80, 402 (1998)

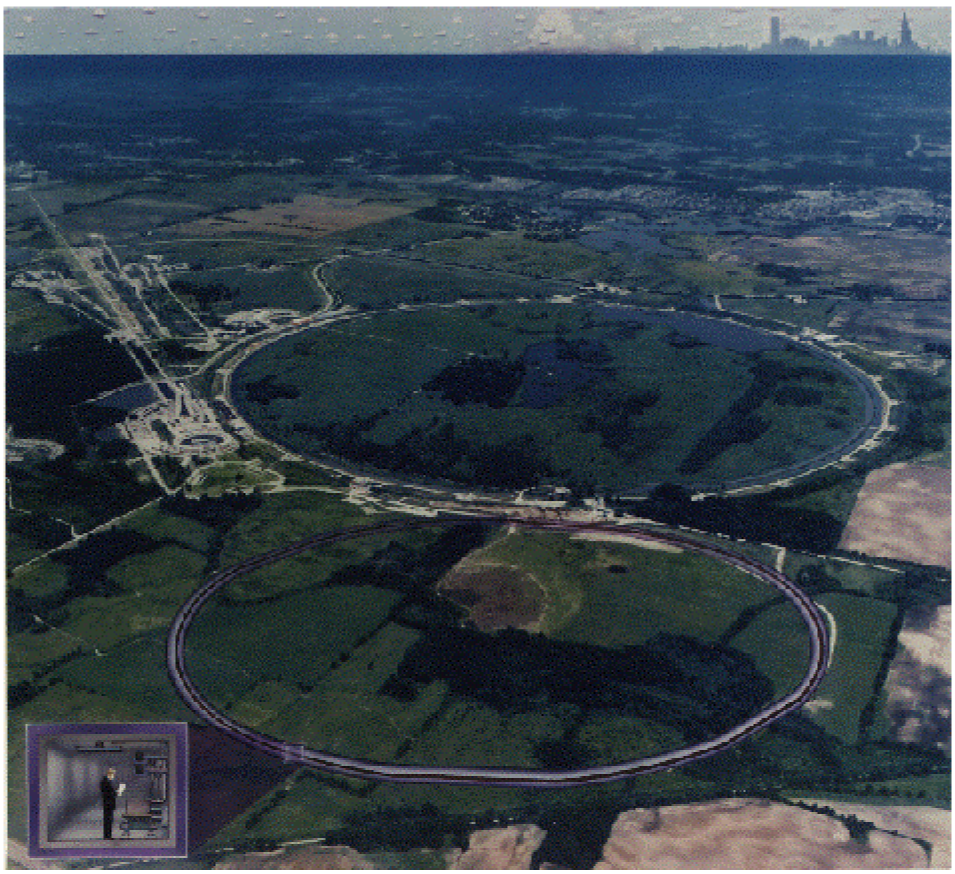


hep-ex/9808010

Tevatron Upgrade

Major upgrade to increase luminosity by improving anti-proton production

Two new machines
Main Injector and Recycler



Run II (2000 - 2002)

$\sqrt{s} = 2.0$ TeV with an expected luminosity 2 fb^{-1}

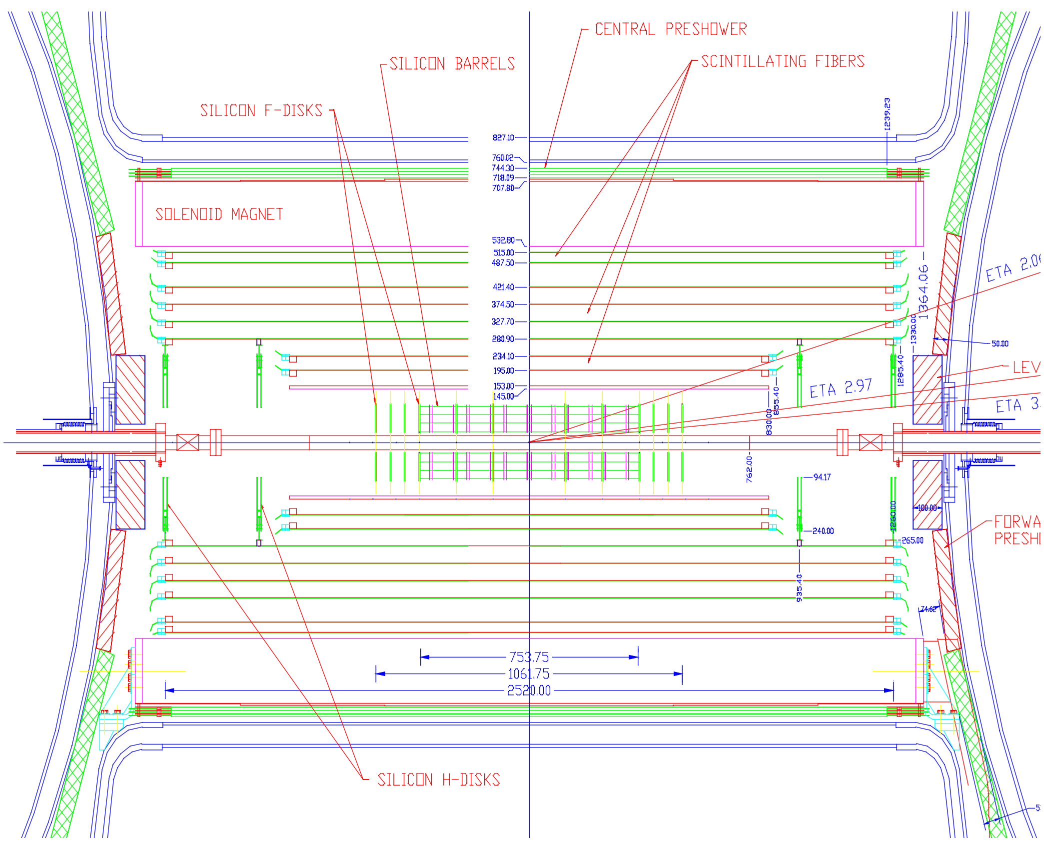
Run III (TeV33) (2003 - ?)

$\sqrt{s} = 2.0$ TeV with an expected luminosity of 30 fb^{-1}

Detector Upgrade

The DØ upgrade is designed to improve
its high p_T capability and
to adapt to the new collider environment

A major part of the upgrade is to replace the
Run I tracker with a magnetic tracker



1) 2 Tesla superconducting solenoid
2) A high resolution silicon vertex detector
3) A state-of-art scintillating fiber tracker
4) Central and forward preshower detectors

Silicon Vertex Detector

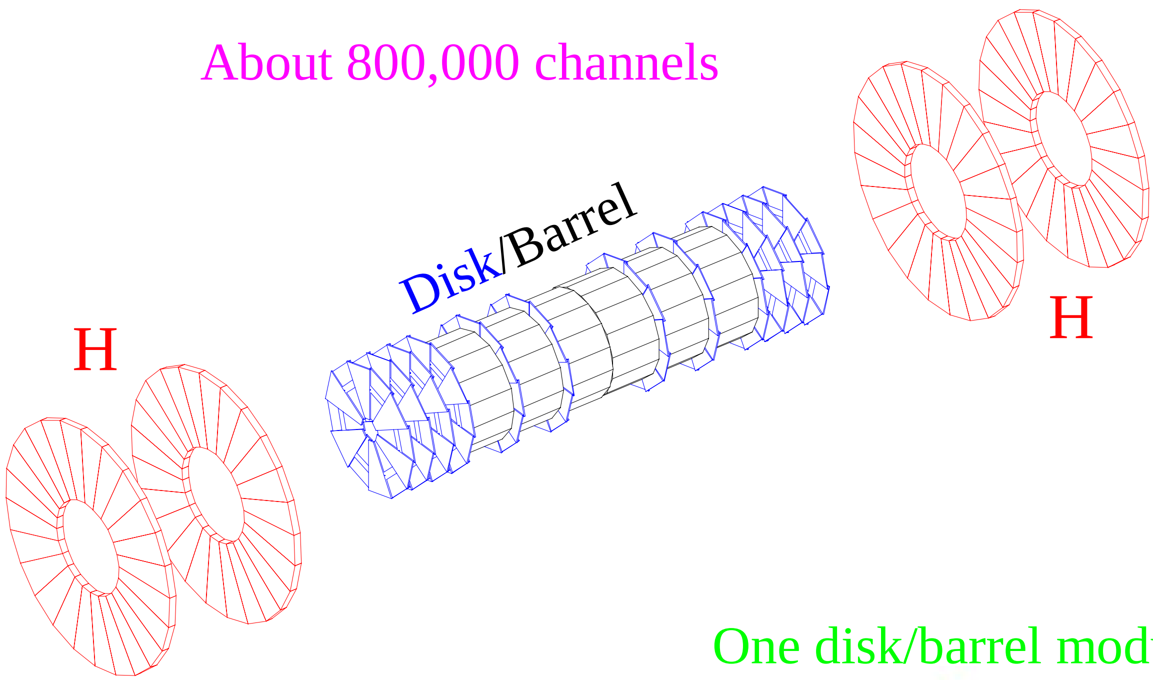
Six 12cm disk/barrel modules

Four layers (single or double sided) per barrel

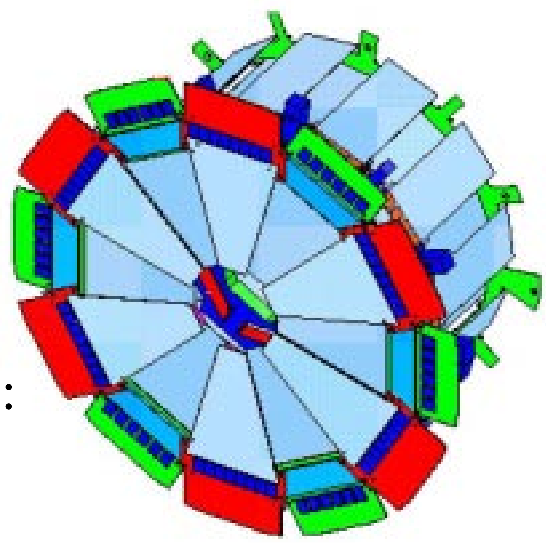
Interspersed double disks with ±15° stereo angles

Four large H disks at forward region

About 800,000 channels



One disk/barrel module



Pitch varies from 50-100 μm

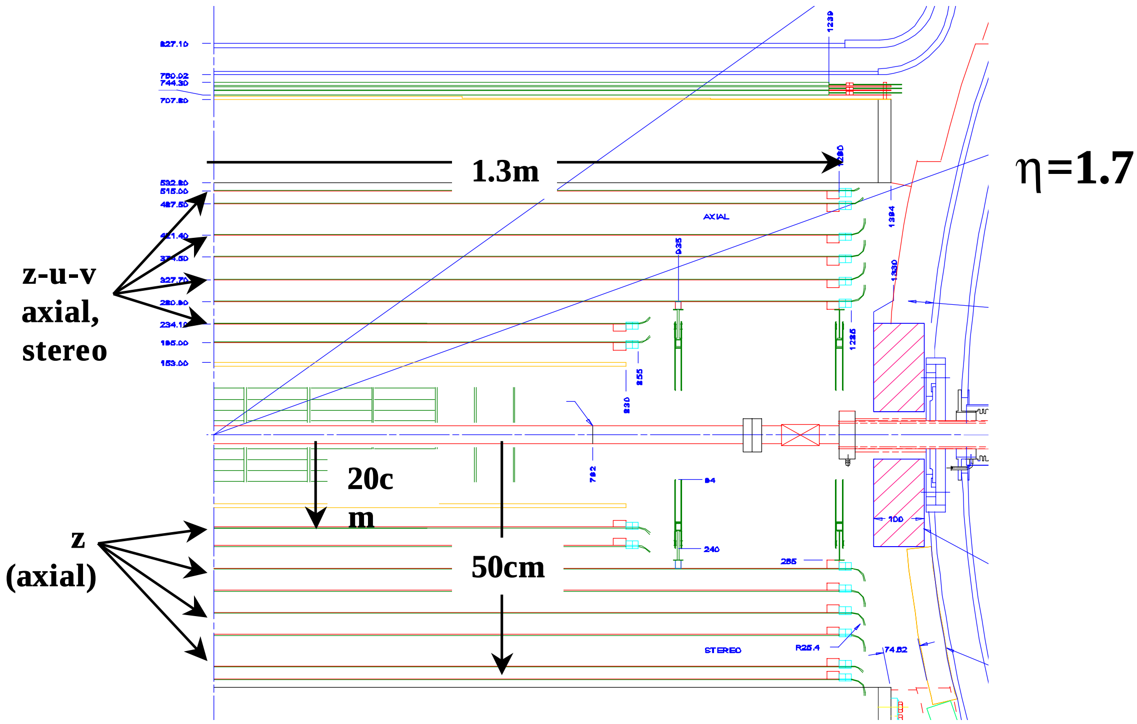
10 μm single hit resolution

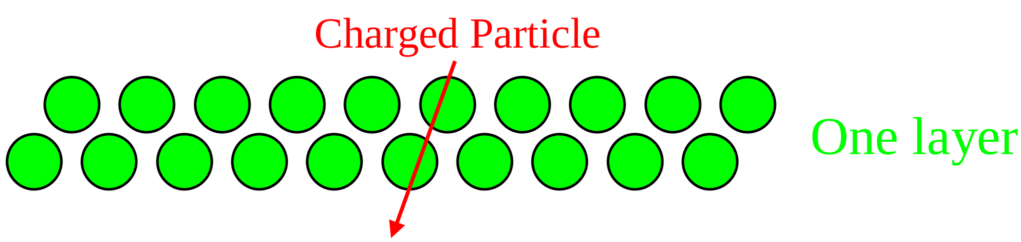
Secondary vertex resolutions:

40 μm in R-ϕ and

100 μm in R-Z

Scintillating Fiber Tracker





16 layers (8 axial and 8 stereo) of scintillating fibers extending radii from 20 to 50 cm.

Fiber diameter: 830 μm,
Single hit resolution: 100 μm

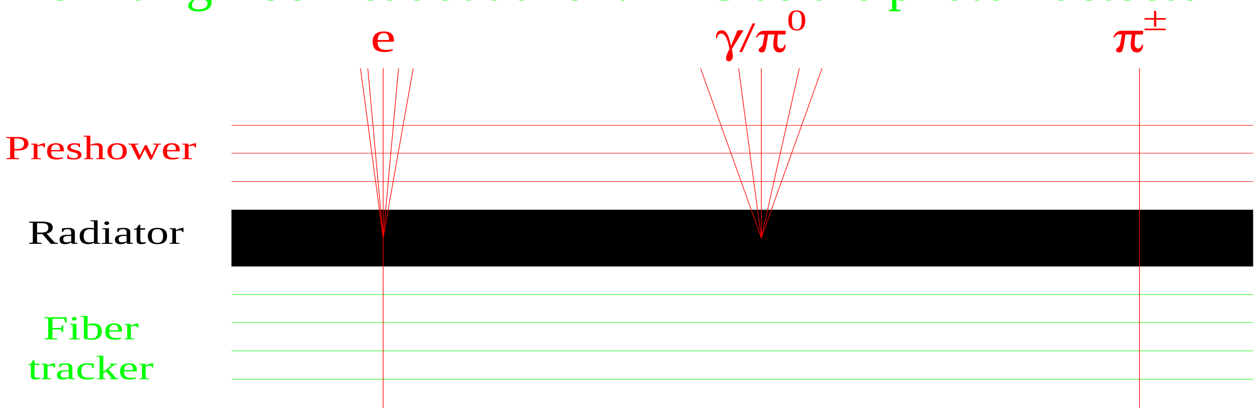
Visible Light Photon Counter (VLPC) as the photodetector, light yield ~ 10 p.e./hit

Total channel count: ~80,000.

Preshower Detectors

Central (8,000 channels) and forward (16,000 channels)
preshower detectors to aid
electron triggering and identification

Extruded triangular strips with embedded wavelength
shifting fiber readout and VLPC as the photon detector



Top Quark Physics

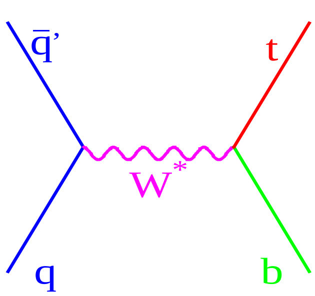
Despite of the discovery, we know little about the
top quark experimentally
due to the small sample of top quark events

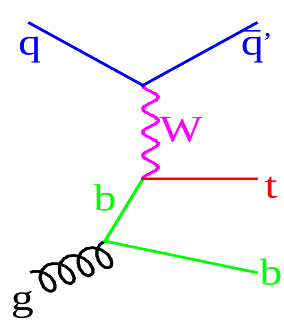
The silicon detector will greatly enhance DØ's
capability for studying top quark physics
A factor of 50 increase in $t\bar{t}$ sample is expected in Run II

With the large top quark sample, we will be able
to study top quark production and decay in detail
and uncover any potential new physics

Due to its heavy mass, $\Gamma_t > \Lambda_{QCD}$
The top quark is the only quark that decays
before hadronization,
$\Rightarrow$ study a `bare' quark for the first time !

Although $\sigma_t \sim \sigma_{t\bar{t}} / 3$ is expected,
single top production has not been positively established





$\sigma_t \propto \Gamma(t \rightarrow bW)$

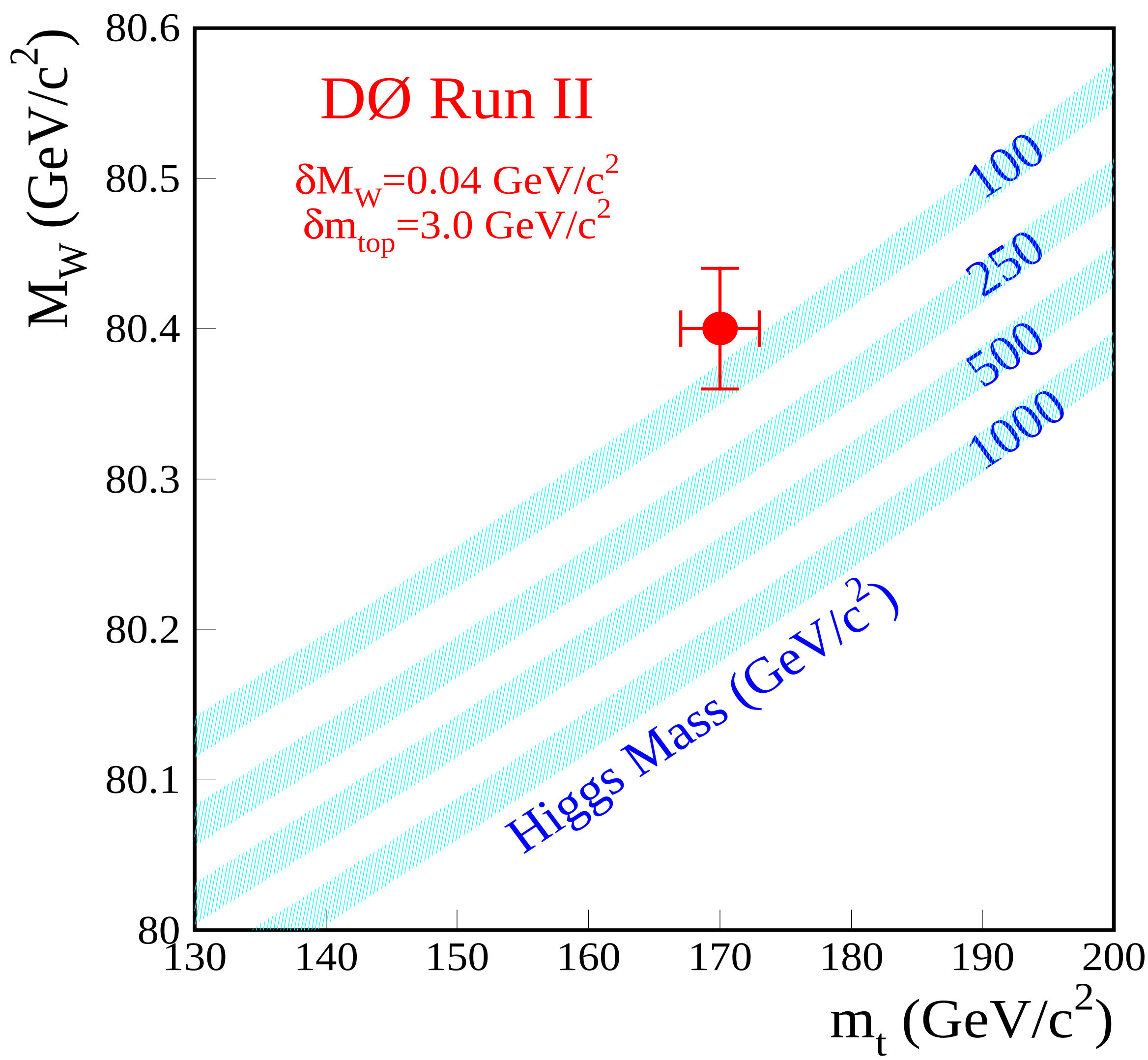
Direct measurement
of top quark width

A rich program in top physics

M_W and m_t Measurements

Statistical and systematic errors contribute equally to the total errors of the present measurements

Most of the errors are expected to scale with $1/\sqrt{N}$
The expected errors from Run II
$\delta M_W = 0.04\ \mathrm{GeV}/c^2 \quad \delta m_t = 3.0\ \mathrm{GeV}/c^2$



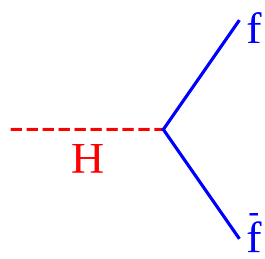
Combined with the data from LEP and SLC, the Higgs mass can be constrained to be within 30%

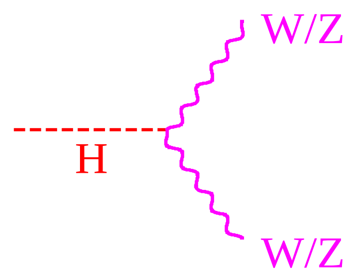
Higgs Boson Decay

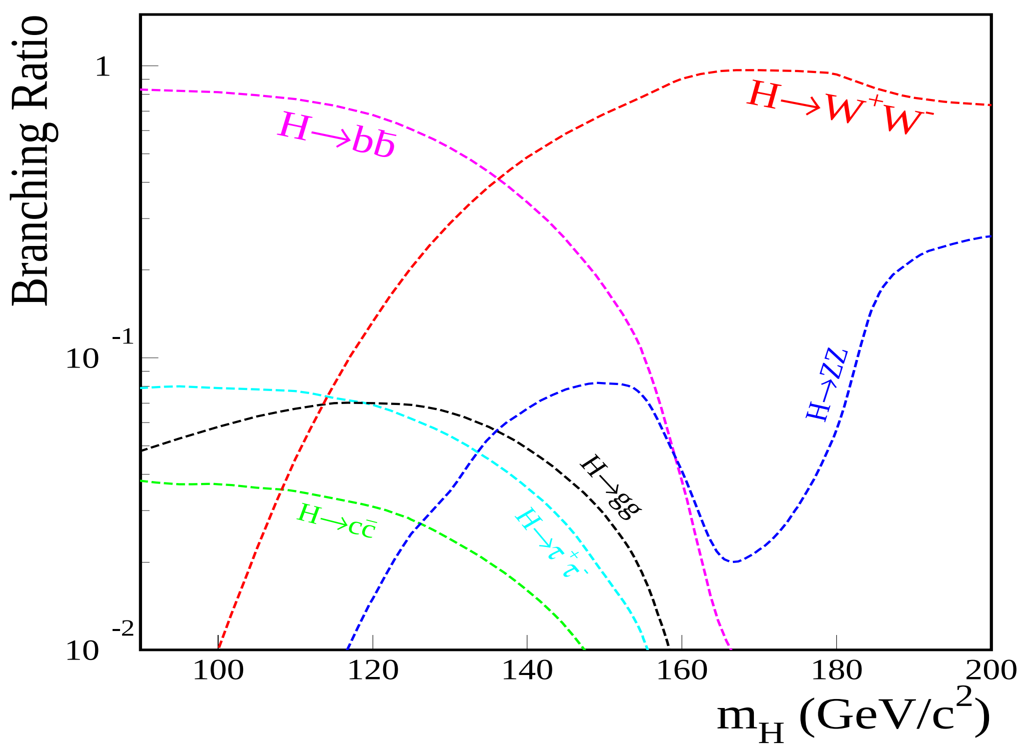
Whenever the kinematics allows, the Higgs boson tends to decay into heavy particles

If $M_H < 120\ \mathrm{GeV}/c^2$, $H \rightarrow b\bar{b}$ dominates
$\Rightarrow$ SM background : QCD $b\bar{b}$ production

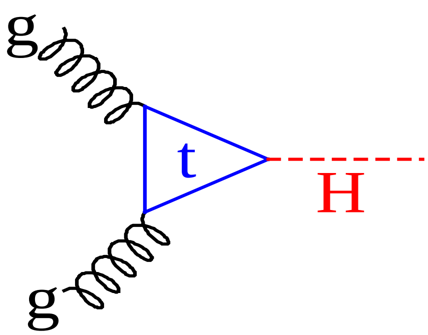
If $M_H > 140\ \mathrm{GeV}/c^2$, $H \rightarrow W^+W^-$ dominates
$\Rightarrow$ SM background : direct W^+W^- production





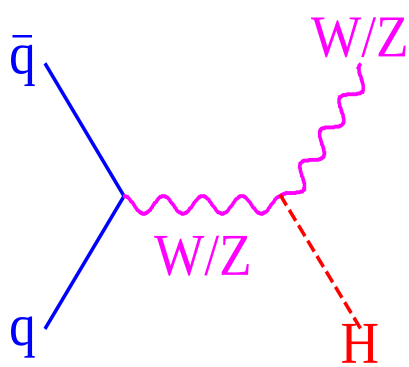


Higgs Boson Production

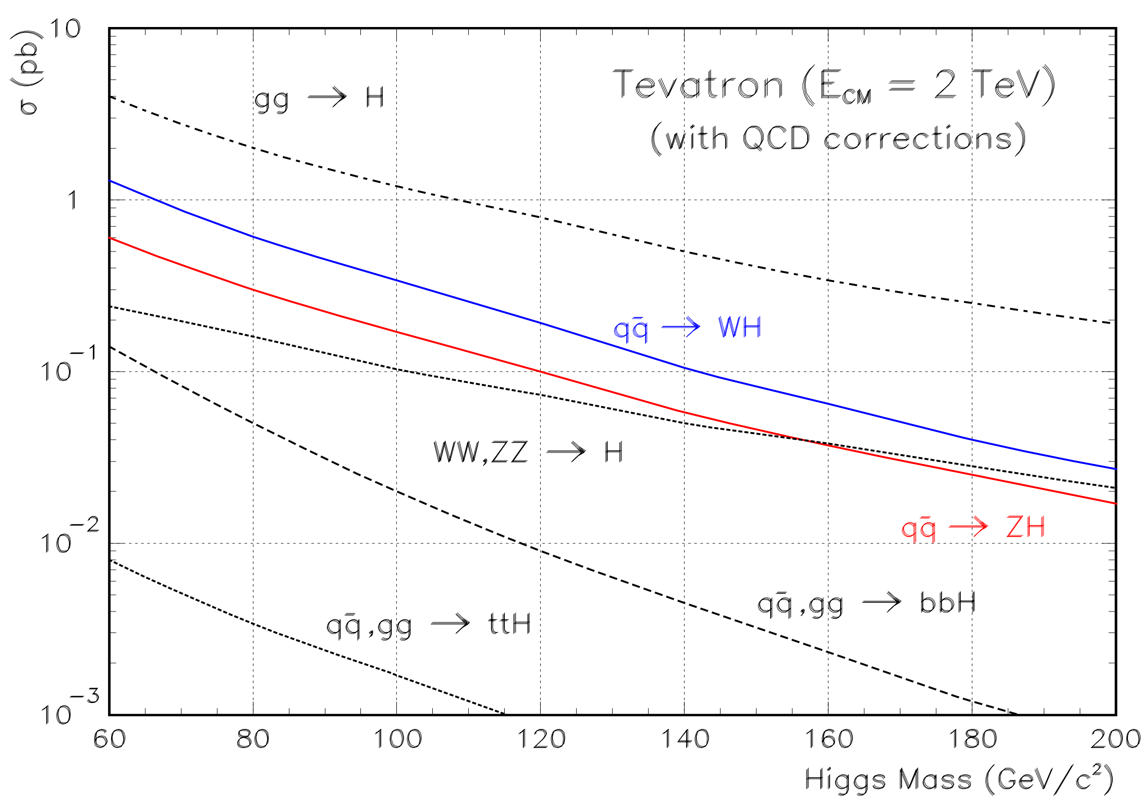


At Tevatron collider, the dominant process for Higgs production is through gluon - gluon fusion $gg \rightarrow H$

However, it has huge SM backgrounds SM $b\bar{b}$ production for $H \rightarrow bb$ and SM W^+W^- production for $H \rightarrow W^+W^-$



WH and ZH production modes have relatively smaller backgrounds



Higgs Boson Search

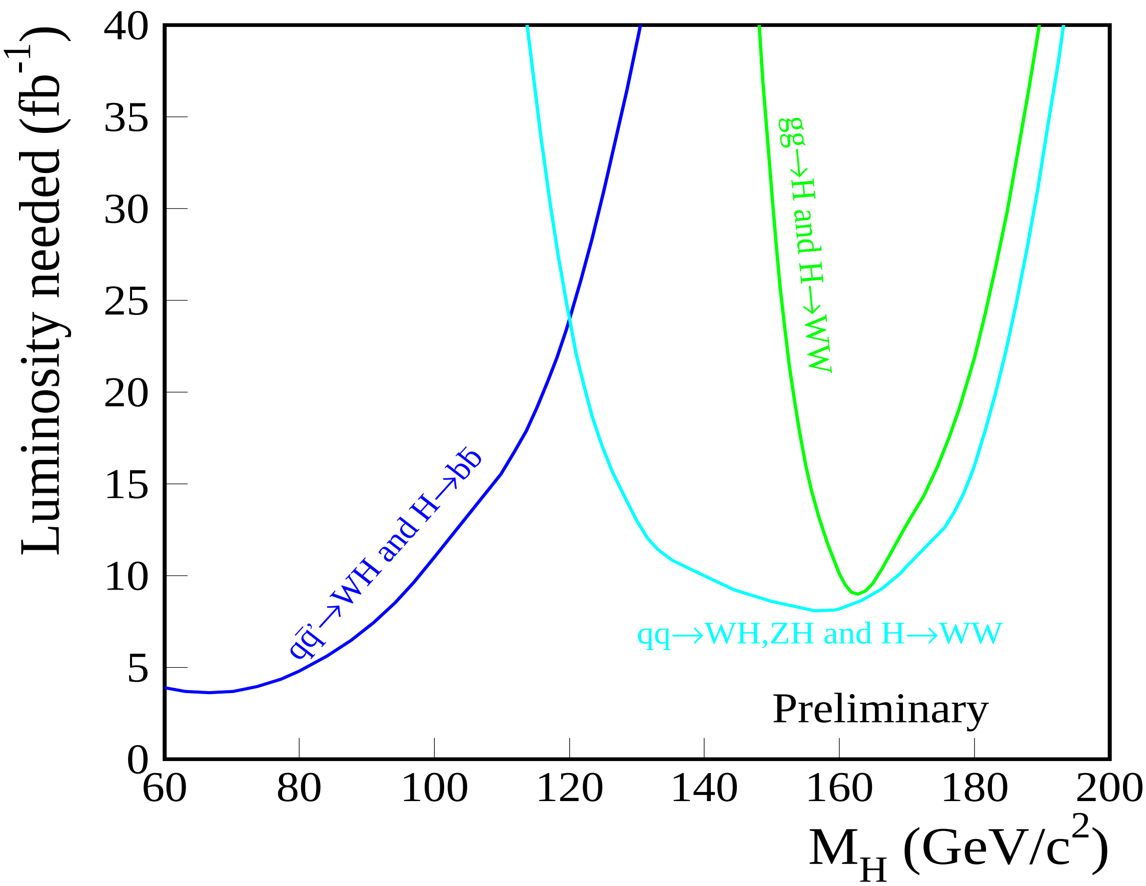
LEP2 will discover or exclude a SM Higgs boson up to 105 GeV/c^2 in mass before Tevatron Run II

Higgs Search at Tevatron

WH, ZH with $H \rightarrow b\bar{b}$ if $m_H < 120$ GeV/c^2

WH, ZH with $H \rightarrow WW^*$ if $m_H > 120$ GeV/c^2

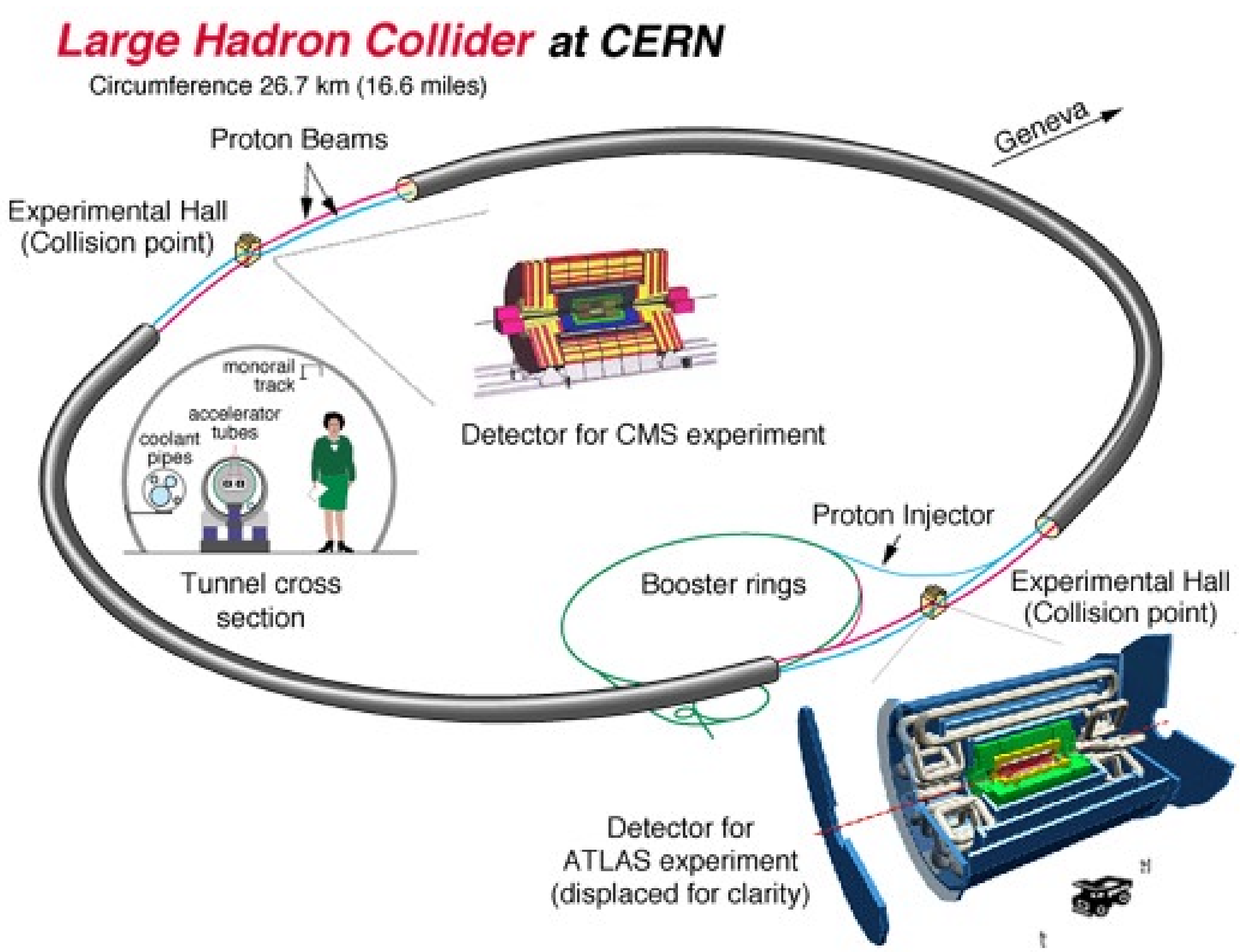
$gg \rightarrow H$ with $H \rightarrow WW^*$ if $m_H > 140$ GeV/c^2



Run III has a realistic chance for discovering or excluding the SM Higgs boson up to 180 GeV/c^2 in mass

Large Hadron Collider

The Large Hadron Collider currently under construction at CERN is scheduled to start operating around 2005 with a center-of-mass energy of 14 TeV.



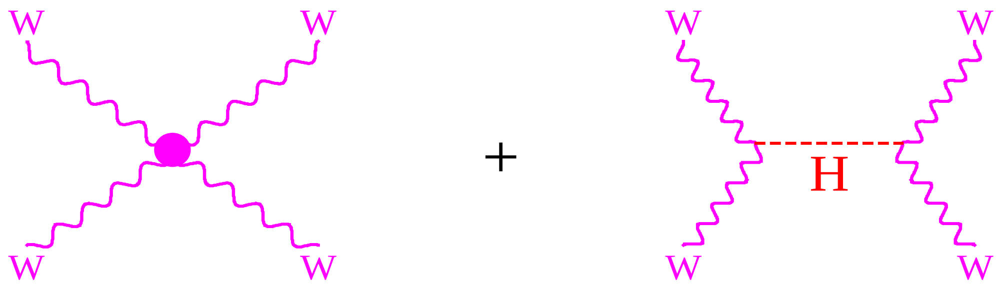
It is our great hope for exploring the TeV scale physics and understanding the puzzle of EW symmetry breaking.

There are two general purpose experiments planned. Michigan is a member of the ATLAS collaboration.

What if There is No Higgs

Not only the Higgs boson is needed for particle masses, it is also needed to make

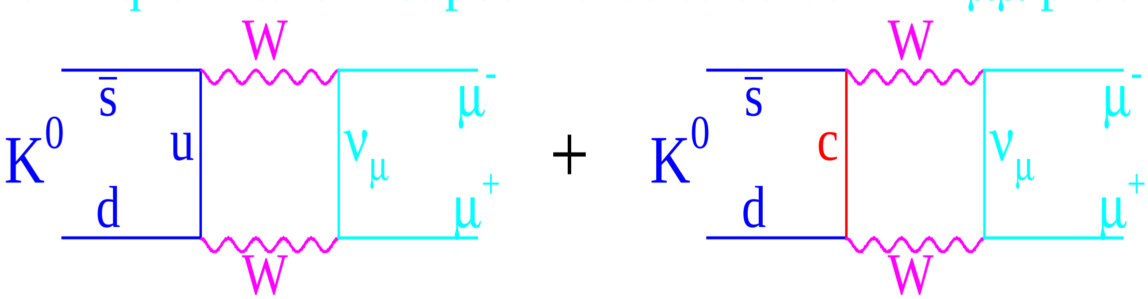
$\sigma\left(W_L^+ W_L^- \to W_L^+ W_L^-\right)$ finite



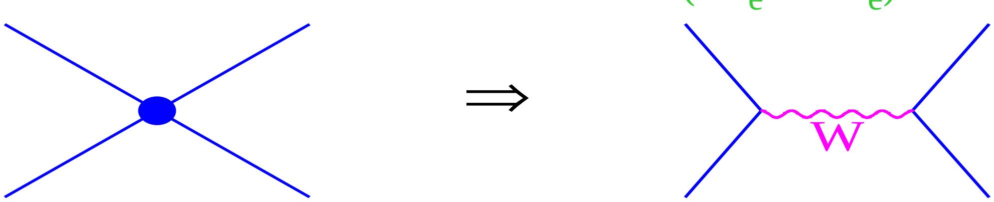
If the Higgs boson does not show up, we expect to see anomaly in WW$\to$WW cross section

Historical Precedent

Charm quark was first postulated to solve $K^0 \to \mu\mu$ problem



W boson was introduced to make $\sigma(e\nu_e \to e\nu_e)$ finite



$$\sigma \Rightarrow \frac{G_F^2\, s}{\pi} \qquad\qquad \sigma \Rightarrow \frac{G_F^2\, M_W^2}{\pi}$$

Summary

Hadron colliders served us well in
our pursue of high p_T, high mass physics

The upgraded Tevatron and
the new LHC will open up
new domains of high energy exploration

What can we expect in the next decade?

Learn a great deal about top quark
and from top quark

Hopeful to unravel the puzzle of
electroweak symmetry breaking

……

Expect for unexpected…

Run I Physics Menu

- Top Quark Physics
  - Discovery of the top quark
  - Measurement of cross section and mass
  - Study of top decay properties
  - Search for single top production
- Electroweak Physics
  - W/Z cross section and p_T distributions
  - Measurement of W mass
  - Triple gauge boson couplings
- Quantum Chromodynamics
  - Jet physics
  - Color coherence
  - Small x physics
- Searches for New Phenomena
  - Search for supersymmetry
  - Search for leptoquarks, compositeness etc
- B Physics
  - Inclusive b production
  - J/ψ production

Selection of $t\bar{t}$ Candidates

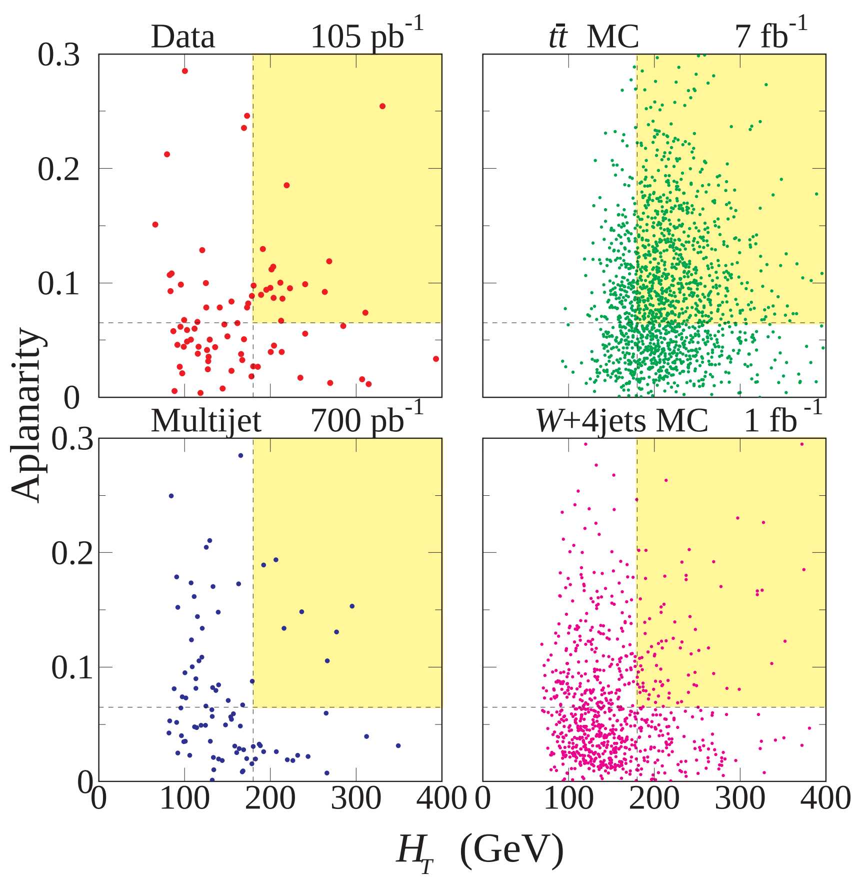
Top pair events are topologically different from
most of the background events.

Top events are expected to be more spherical than
most of the QCD background events.
All top events have two b-quark jets.

Di- and single-lepton events have high E_T leptons, large $\not{E}_T$

Sophisticated criteria were developed to distinguish
top pair events from the huge number of background events

Selection of ℓ + jets events



Supersymmetry

To supersymmetrize the Standard Model,
the Higgs fields are doubled leading to five Higgs particles

Standard Model Particles

$W^{\pm} H^{\pm}$ γ Z h H A u d e ν ......

$\Downarrow$ $\Downarrow$ $\Downarrow$

$\tilde{\chi}_2^{\pm}$ $\tilde{\chi}_1^{\pm}$ $\tilde{\chi}_4^0$ $\tilde{\chi}_3^0$ $\tilde{\chi}_2^0$ $\tilde{\chi}_1^0$ $\tilde{u}_L$ $\tilde{d}_L$ $\tilde{e}_L$ $\tilde{\nu}_L$ $\tilde{u}_R$ $\tilde{d}_R$ $\tilde{e}_R$ $\tilde{\nu}_R$ $\widetilde{......}$

Supersymmetric Particles

Most supersymmetry models assume that R-parity
(R=+1 for the SM particles and R=–1 for their partners)
is conserved

1) supersymmetric particles are pair produced
2) heavy sparticles decay to lighter sparticles
3) the Lightest Supersymmetric Particle (LSP) is stable
$\Rightarrow$ missing transverse energy ($\not{E}_T$)

Events with large $\not{E}_T$ are expected from
the production of supersymmetric particles

Proposed Theoretical Models

In Gauge Mediated Models with NLSP=$\tilde{\chi}_1^0$

$\tilde{\chi}_1^0 \to \gamma\, \tilde{G}$

$p\bar{p} \to \tilde{\chi}^+ \tilde{\chi}^- \to W^+ W^- \tilde{\chi}_1^0 \tilde{\chi}_1^0$

$p\bar{p} \to \tilde{e}\tilde{e} \to ee\tilde{\chi}_1^0 \tilde{\chi}_1^0$

were proposed as possible explanations of the event

Ellis et al., PLB 394 (1997), Ambrosanio et al., PRD 54, 5395 (1996), ...

Pair production of any supersymmetric particles will result in $\gamma\gamma \not{E}_T$+X events if both $\tilde{\chi}_1^0$ decay inside the detector

Within the framework of MSSM with the LSP=$\tilde{\chi}_1^0$, a class of models with dominant

$\tilde{e} \to e + \tilde{\chi}_2^0$ and $\tilde{\chi}_2^0 \to \tilde{\chi}_1^0 + \gamma$

decays was also proposed as an explanation of the event

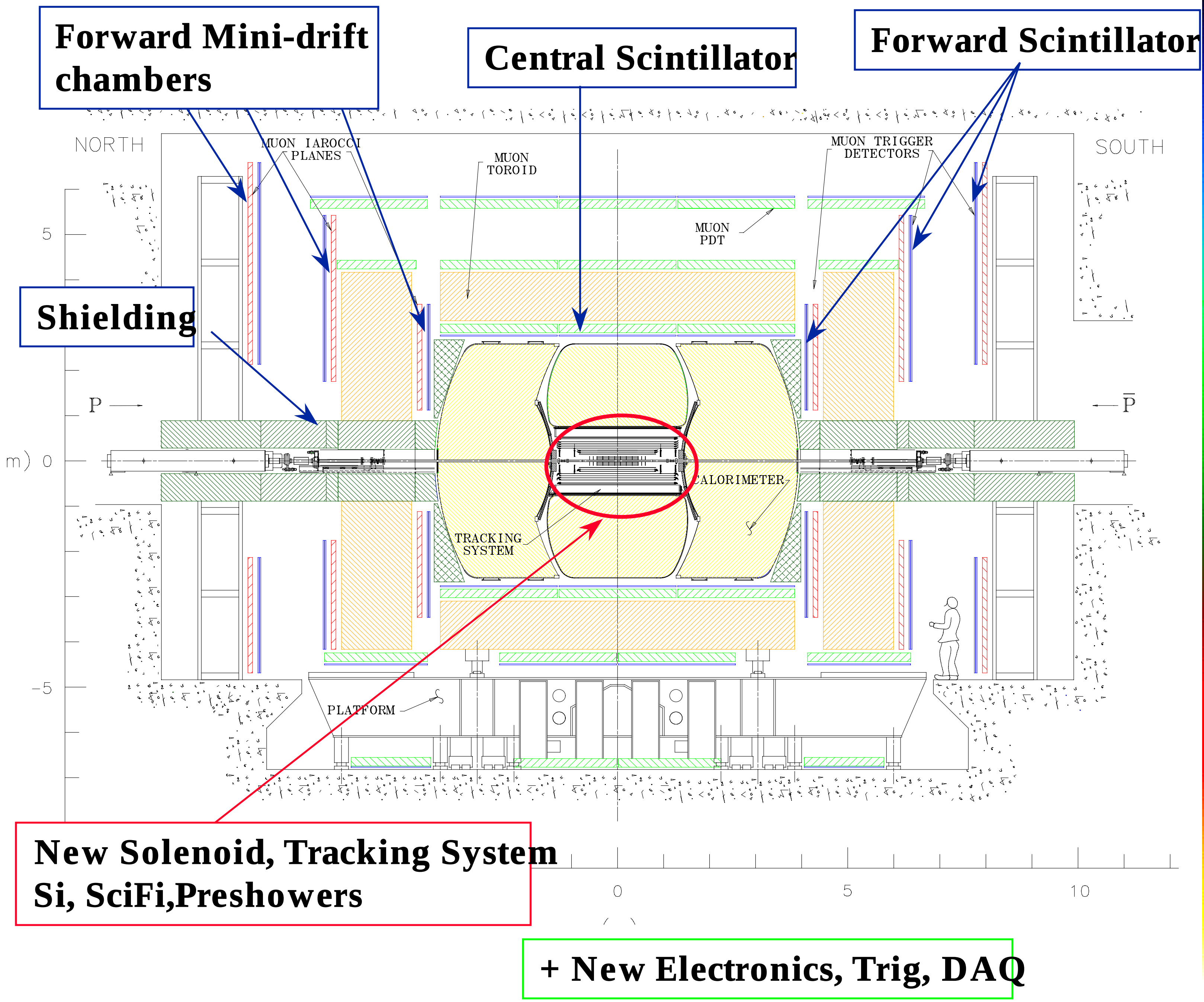
$p\bar{p} \to \tilde{e}\tilde{e} \to ee\tilde{\chi}_2^0 \tilde{\chi}_2^0 \to ee\gamma\gamma\tilde{\chi}_1^0 \tilde{\chi}_1^0$

Kane et al., Phys. Rev. D55, 1372 (1997)

$\gamma\gamma \not{E}_T$ events are expected from $p\bar{p} \to \tilde{e}\tilde{e}$, $\tilde{\nu}\tilde{\nu}$, $\tilde{\chi}_2^0 \tilde{\chi}_2^0$+X processes

$\gamma \not{E}_T$+jets events are expected from $p\bar{p} \to \tilde{q}/\tilde{g} \to \tilde{\chi}_2^0$+X processes

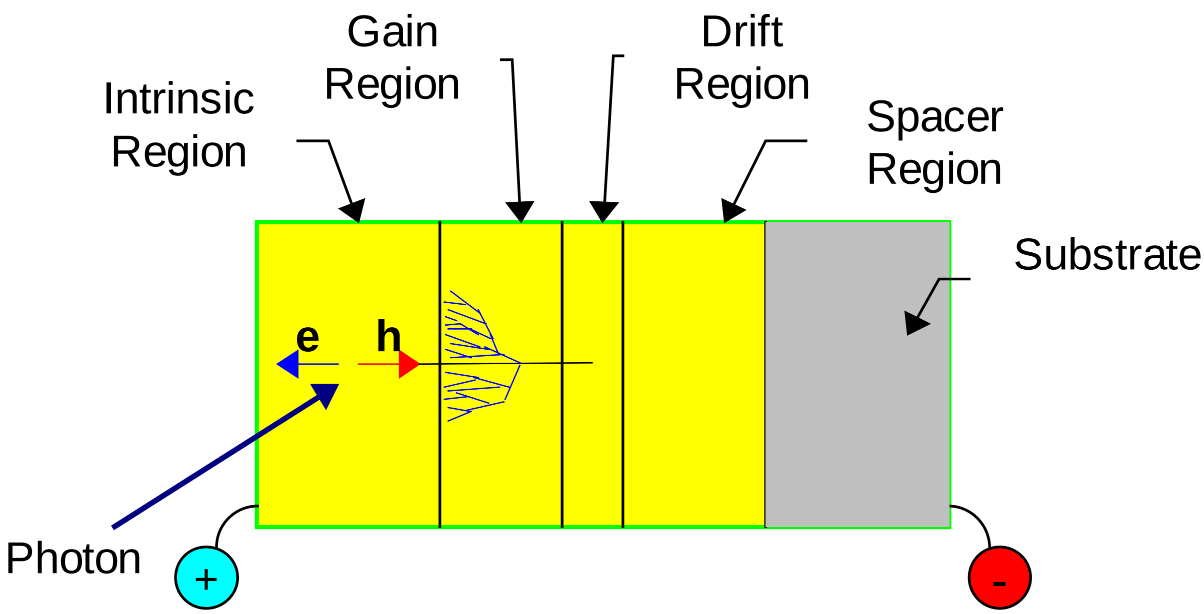
Detector Upgrade

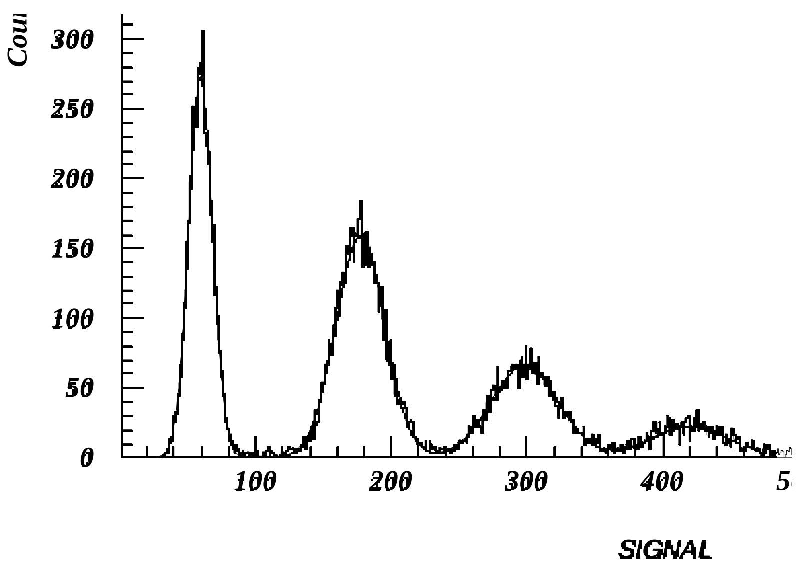


Visible Light Photon Counter

VLPC is a solid state detector which operates at 5K
with a quantum efficiency of 70% and
a gain of 30,000.

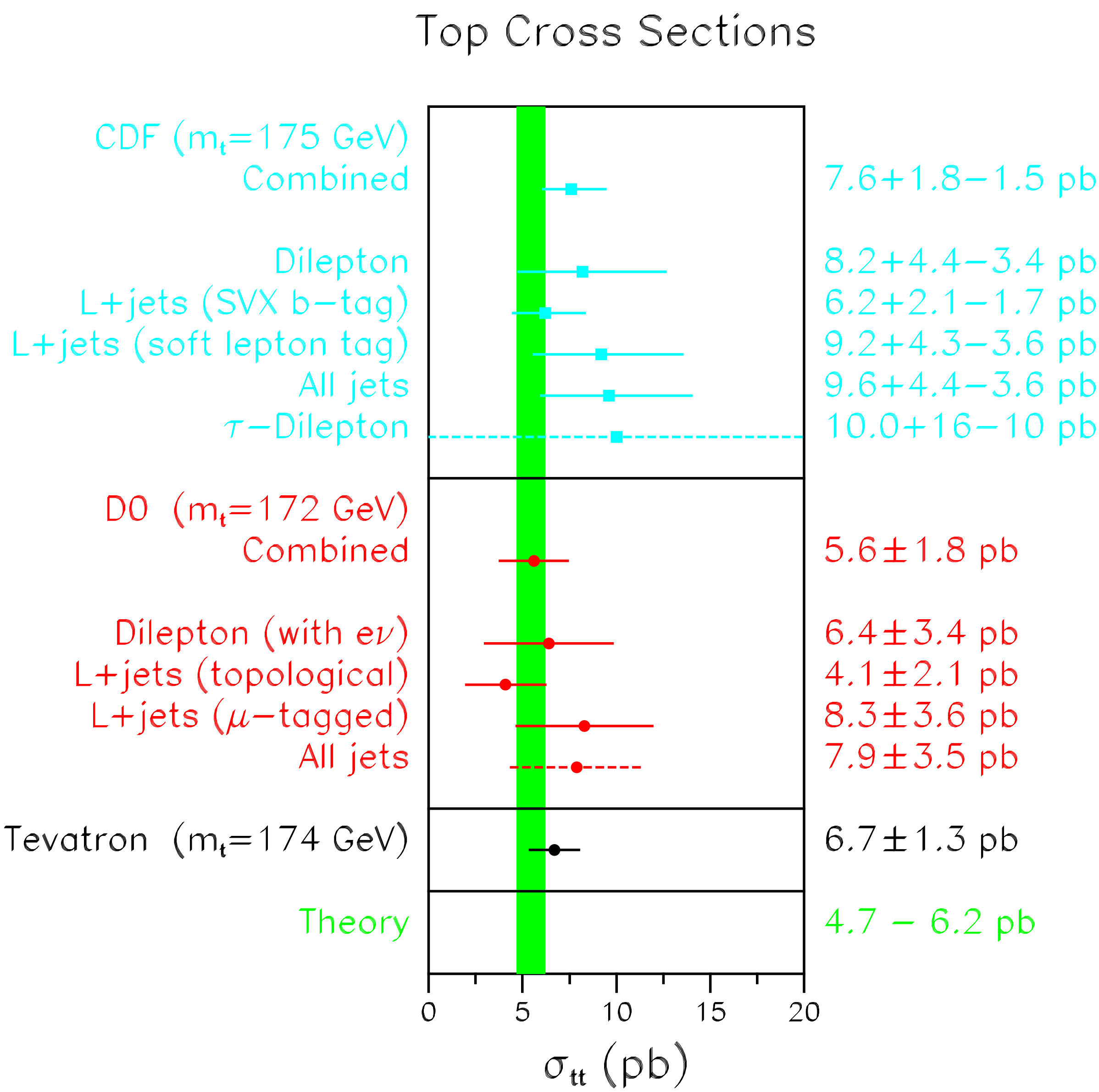
The sensitivity peaks around 500 nm (Green).



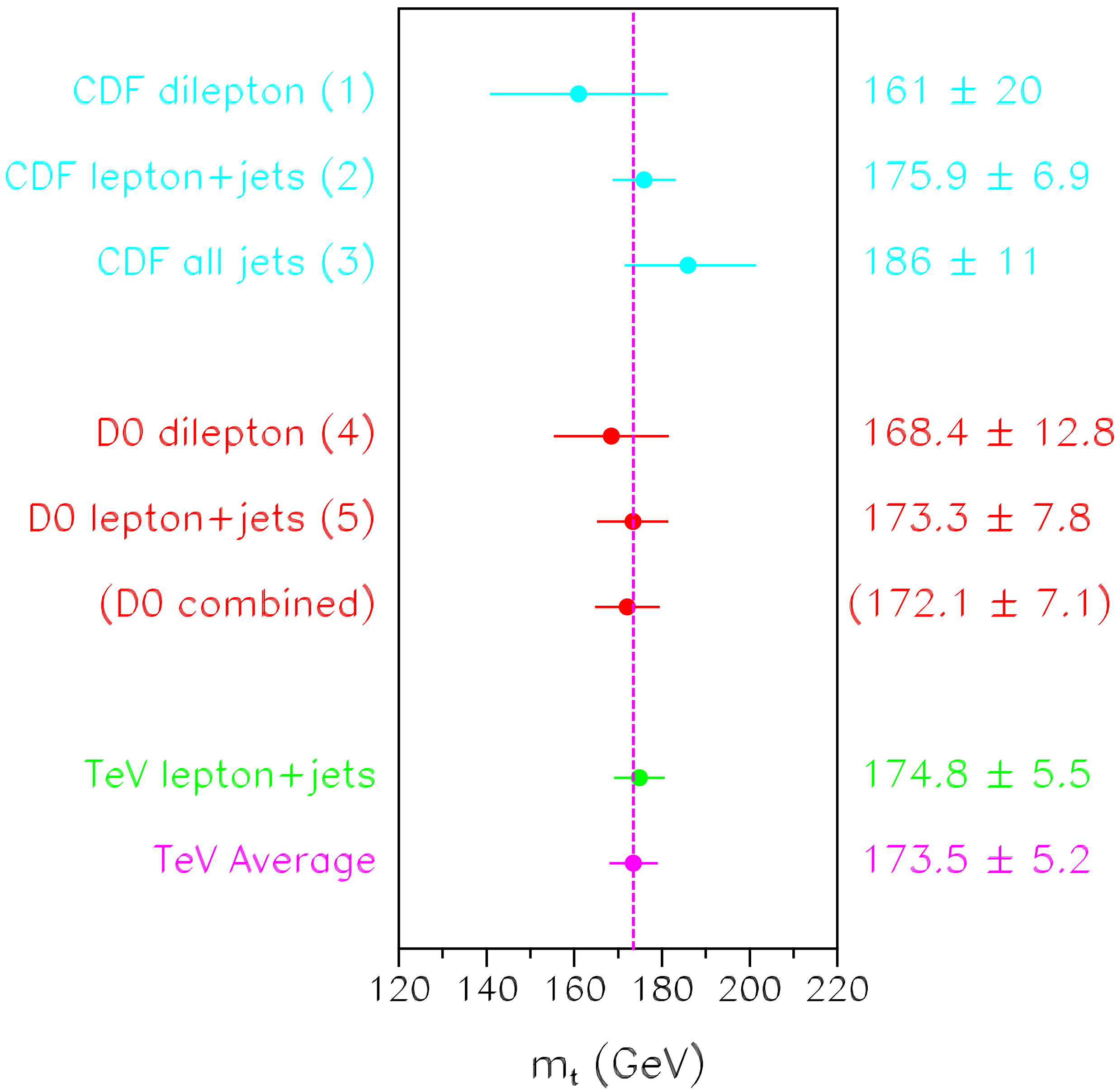


Capable of single photon counting !

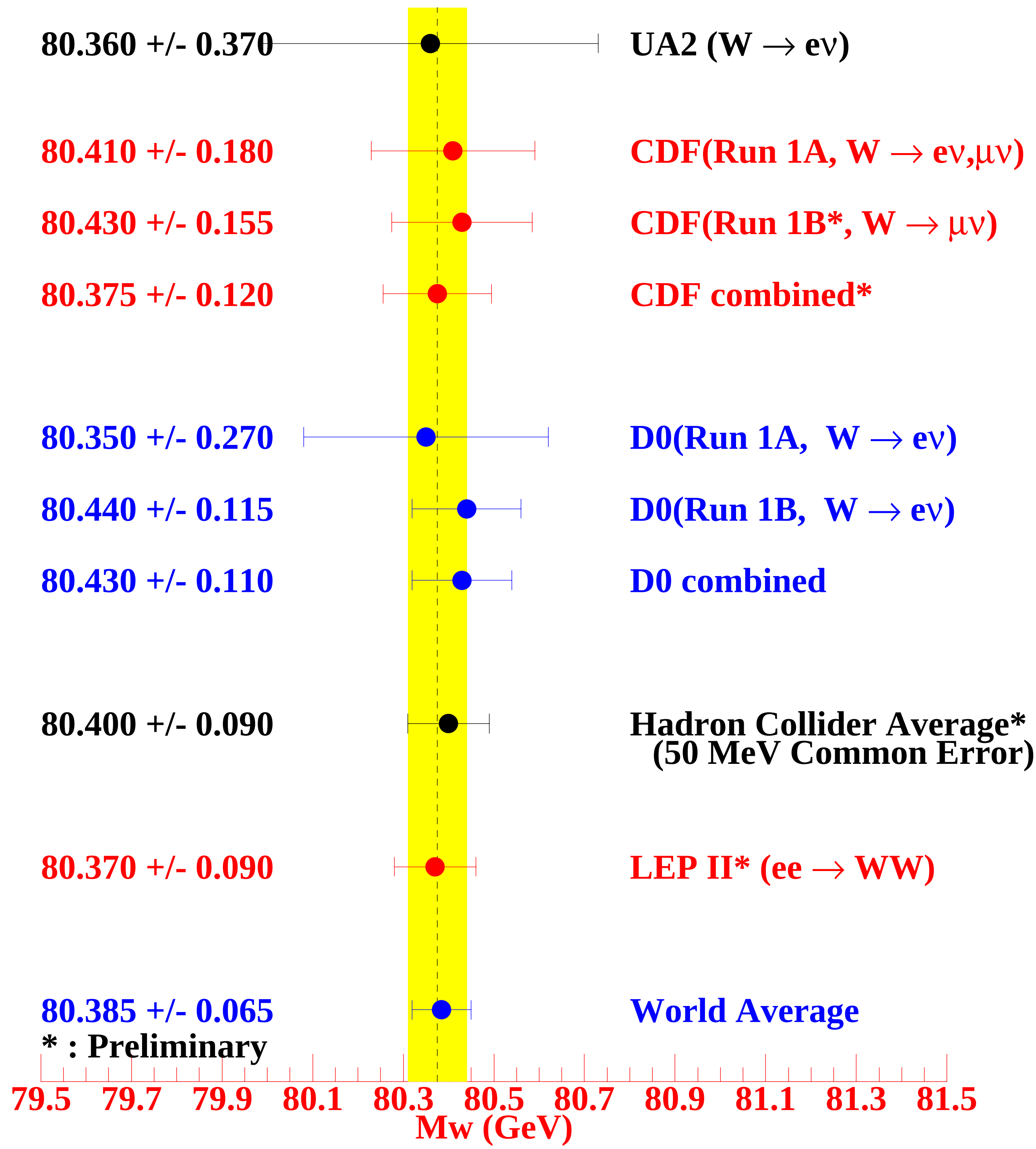
Tevatron Top Pair Cross Section



Tevatron Top Quark Mass



World W Boson Mass



Three Light Neutrino Species